Status of Vermilion rockfish (*Sebastes miniatus*) along the US West - Washington State coast in 2021

by
Jason M. Cope[1]
Tien-Shui Tsou[2]
Kristen Hinton[2]
Corey Niles[2]

[1]Northwest Fisheries Science Center, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 2725 Montlake Boulevard East, Seattle, Washington 98112
[2]Washington Department of Fish and Wildlife, 600 Capital Way North, Olympia, Washington 98501

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Executive Summary

Stock

This assessment reports the status of vermilion rockfish (*Sebastes miniatus*) off Washington state using data through 2020. Vermilion rockfish are also found in California and Oregon waters, but those are treated separately in other stock assessments. The core range of vermilion rockfish are in California, thus outside Washington waters; this assessment thus considers a very small population at the limit of the species range under different mangement considerations and exploitation histories than vermilion rockfish stocks in either California or Oregon. There is substantial biogeographic separation in the populations off Oregon and Washington, thus justifying separation of those populations into different management units and stock assessments. Vermilion in Canadian waters are also rare and not included in this assessment.

Landings

Vermilion rockfish are mainly caught in recreational fisheries by hook and line gear (Figure i). Recreational catches are generally low, but in relative terms increased in mid-1980s and have fluctuated since to a peak catch in 2019 (Table i). Vermilion are not targets in the Washington recreational fishery and are considered rare.

Table i: Recent fishery and total landings (in 1000s of fish).

Year	Fishery	Total Landings
2011	0.518	0.518
2012	0.489	0.489
2013	0.538	0.538
2014	0.534	0.534
2015	0.673	0.673
2016	0.416	0.416
2017	0.491	0.491
2018	0.621	0.621
2019	1.294	1.294
2020	0.325	0.325

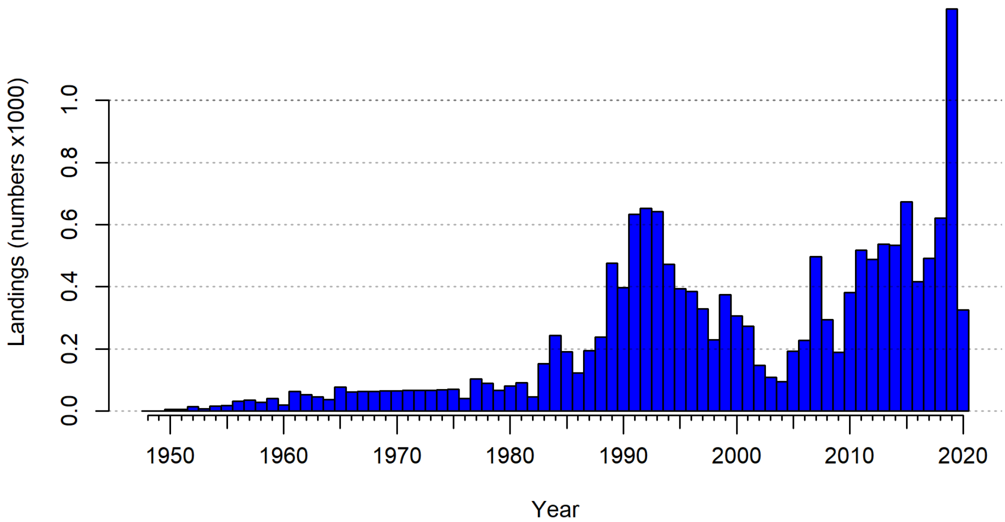

Figure i: Landings (1000s of fish) used in the reference model.

Data and Assessment

The stock assessment for vermilion rockfish off Washington state was developed using the length- and age-structured model Stock Synthesis (version 3.30.16). No previous stock assessment for vermilion rockfish off Washington has been conducted. Model structure included one recreational fleet. Life history parameters were sex-specific (i.e., a two-sex model) with natural mortality and growth parameters estimated, along with recruitment. The model covers the years 1949 to 2020, with a 12 year forecast beginning in 2021.

This assessment integrates data and information from multiple sources into one modeling framework. Specifically, the assessment uses recreational landings data, and length and conditional age-at-length composition data (using ageing error matrices to incorporate ageing imprecision); fixed parameterizations of weight-at-length, maturity-at-length, and fecundity-at-length, the Beverton-Holt stock-recruitment steepness value and recruitment variability. Estimated values include initial population scale (lnR_0), sex-specific natural mortality and growth, asymptotic selectivity and recruitment deviations. The base model was tuned to account for the weighting of the length and age data, as well as the specification of recruitment variance and recruitment bias adjustments. Derived quantities include the time series of spawning output, age and size structure, and current and projected future stock status.

Uncertainty is explicitly included in this assessment through variances of all estimated parameters, while among model uncertainty is explored through sensitivity analyses such as data treatment and weighting, and model specification sensitivity to the treatment of life history parameters, selectivity, and recruitment. A reference model was selected that best fit the observed data while concomitantly balancing the desire to capture the central tendency across those sources of uncertainty, ensure model realism and tractability, and promote robustness to potential model misspecification.

Stock Biomass

Spawning output (in millions of eggs; meggs) instead of spawning biomass is used to report the mature population scale because fecundity is nonlinearly related to female body weight. The estimated spawning output at the beginning of 2021 was 2 meggs (~95 percent asymptotic intervals: -1 to 4 meggs, Table ii and Figure ii), which when compared to unfished spawning biomass (3) meggs gives a relative stock status level of 56 percent (~95 percent asymptotic intervals: 6 to 107 percent, Figure iii). Overall, spawning output declined with the onset of increasing recreational removals in the mid-1980s and continued to decline with the increase in recreational catches through the 1990s. The largest of the estimated recruitment pulses since the late 1990s (that are supported by each of the data sets) caused a small increase in the spawning output through the early 2010s, after which a very small decline is observed. The minimum relative stock size of 55 percent of unfished levels is estimated to have occurred in 2002. Currently the stock is estimated to be above the management target of $SB_{40\%}$ in 2021 and has never dropped below the target throughout the time series (Table ii and Figure iii).

Table ii: Estimated recent trend in spawning output and the fraction unfished and the 95 percent intervals.

Year	Spawning Output	Lower Interval	Upper Interval	Fraction Unfished	Lower Interval	Upper Interval
2011	1.82	<0.01	3.89	0.66	0.36	0.97
2012	1.82	<0.01	3.94	0.66	0.34	0.99
2013	1.81	<0.01	3.98	0.66	0.32	1.00
2014	1.81	<0.01	4.02	0.66	0.30	1.02
2015	1.80	<0.01	4.06	0.66	0.28	1.04
2016	1.77	<0.01	4.08	0.64	0.24	1.05
2017	1.77	<0.01	4.13	0.65	0.23	1.07
2018	1.76	<0.01	4.15	0.64	0.20	1.08
2019	1.72	<0.01	4.14	0.62	0.17	1.08
2020	1.56	<0.01	3.99	0.57	0.07	1.07
2021	1.55	<0.01	4.00	0.56	0.06	1.07

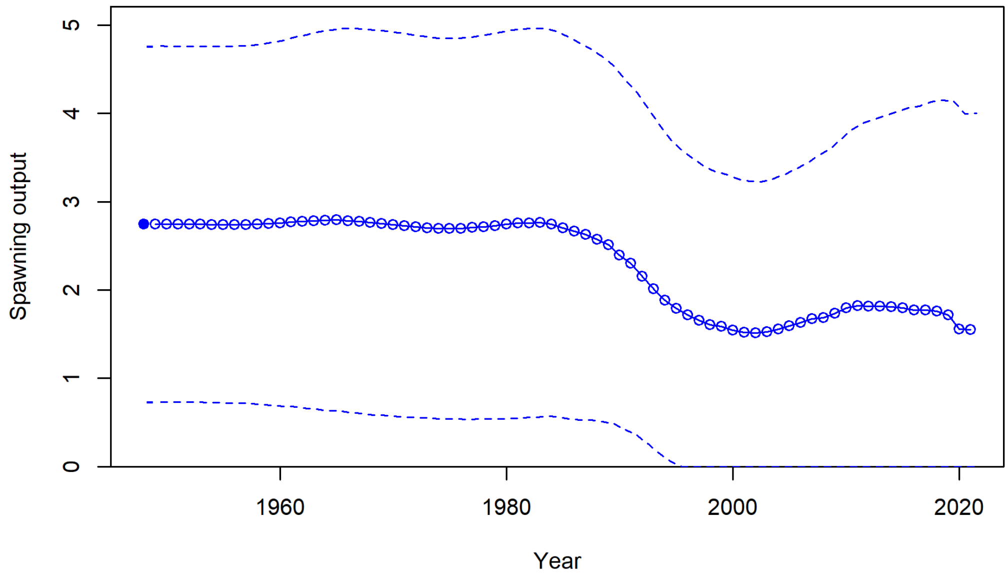

Figure ii: Estimated time series of spawning output (circles and line: median; light broken lines: 95 percent intervals) for the base model.

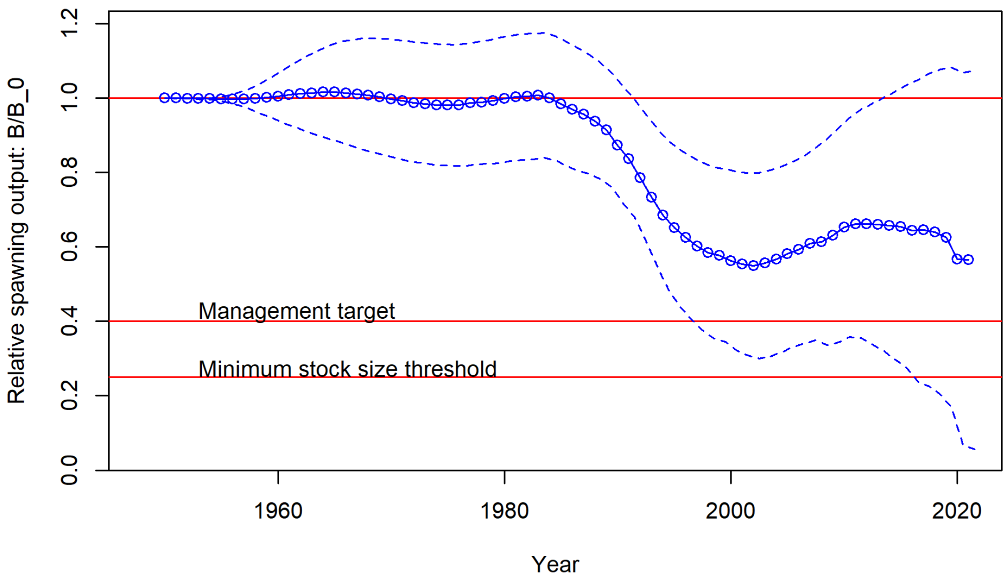

Figure iii: Estimated time series of fraction of unfished spawning output (circles and line: median; light broken lines: 95 percent intervals) for the base model.

Recruitment

Recruitment information is overall weak for this model; informative recruitments start to appear in the 1980s and peak in early 2000s (Table iii and Figure iv). Data were most informative from the 1990s to the mid-2010s. Peak years of recruitments are found in years 1995-1996, 1999-2000, 2006, and 2011 (Figure v). Overall, the vermilion rockfish stock has not been reduced to levels that would provide considerable information on how recruitment compensation changes across spawning biomass levels (i.e., inform the steepness parameter). Thus, all recruitment is based on a fixed assumption about steepness (h = 0.72) and recruitment variability (σ_R = 0.6).

Table iii: Estimated recent trend in recruitment (1000s of fish) and recruitment deviations and the 95 percent intervals.

Year	Recruitment	Lower Interval	Upper Interval	Recruitment Deviations	Lower Interval	Upper Interval
2011	2.97	0.72	12.36	0.30	-0.56	1.15
2012	1.77	0.42	7.56	-0.23	-1.20	0.74
2013	1.63	0.38	6.93	-0.33	-1.32	0.66
2014	1.81	0.42	7.77	-0.24	-1.28	0.81
2015	1.94	0.45	8.47	-0.18	-1.28	0.92
2016	2.24	0.50	9.95	-0.04	-1.19	1.10
2017	2.35	0.53	10.53	-0.01	-1.17	1.16
2018	2.35	0.52	10.56	-0.01	-1.17	1.16
2019	2.35	0.52	10.56	-0.01	-1.17	1.16
2020	2.32	0.51	10.55	-0.01	-1.17	1.16
2021	2.33	0.51	10.55	0.00	-1.18	1.18

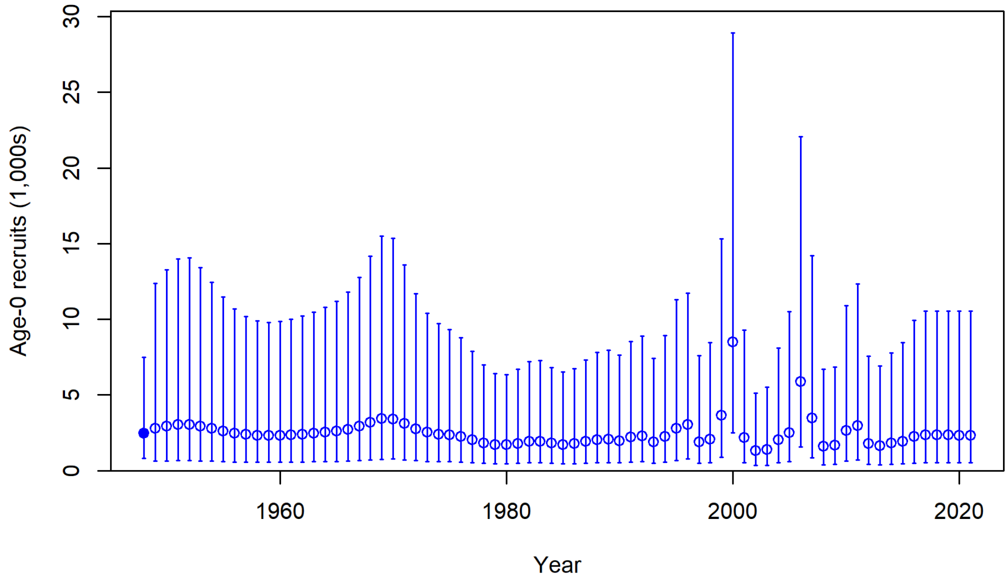

Figure iv: Estimated time series of age-0 recruits (1000s) for the base model with 95 percent intervals.

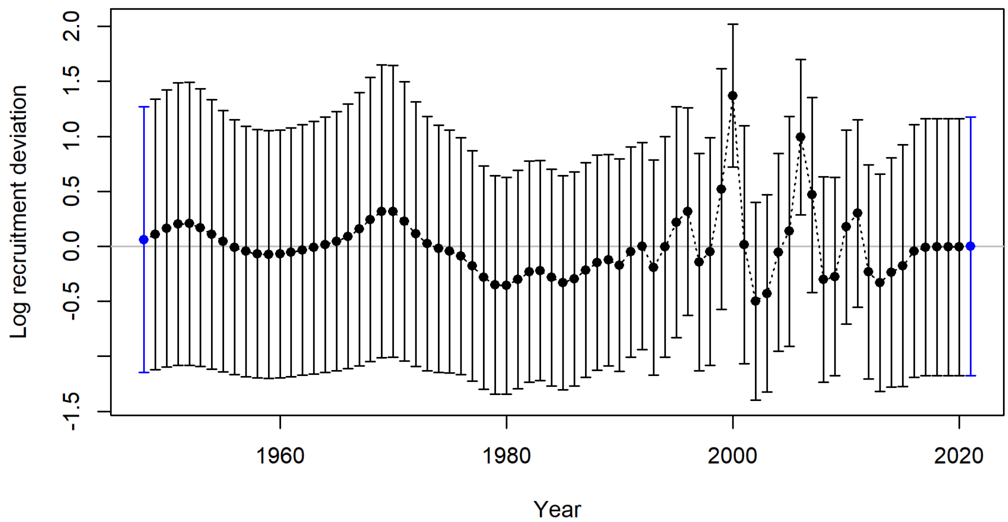

Figure v: Estimated time series of recruitment deviations.

Exploitation Status

Trends in fishing intensity (1 - SPR) largely mirrored that of landings (Table iv; Figure vi). The maximum fishing intensity was 0.75 in 2019, above the target SPR-based harvest rate of 0.50 (1 - $SPR_{50\%}$). Current levels of 0.4 for 2020 are below the retrospectively estimated fishing limit, but 2019 was the highest on record. Fishing intensity over the past decade has ranged between 0.4 and 0.75 and the exploitation rate has been moderate (0.04 - 0.14, Table iv). Current estimates indicate that vermilion rockfish spawning output is greater than than the target biomass level ($SB_{40\%}$), though fishing intensity has fluctuated near target F_{MSY} proxy harvest rate.

Table iv: Estimated recent trend in the 1-SPR where SPR is the spawning potential ratio the exploitation rate, and the 95 percent intervals.

Year	1-SPR	Lower Interval	Upper Interval	Exploitation Rate	Lower Interval	Upper Interval
2011	0.47	0.09	0.84	0.05	0.00	0.10
2012	0.45	0.08	0.83	0.04	0.00	0.10
2013	0.48	0.09	0.87	0.05	0.00	0.11
2014	0.48	0.08	0.88	0.05	0.00	0.11
2015	0.55	0.14	0.96	0.06	0.00	0.14
2016	0.42	0.02	0.82	0.04	0.00	0.09
2017	0.47	0.05	0.89	0.05	0.00	0.11
2018	0.54	0.10	0.98	0.06	0.00	0.14
2019	0.75	0.38	1.12	0.14	0.00	0.33
2020	0.40	0.00	0.84	0.04	0.00	0.09

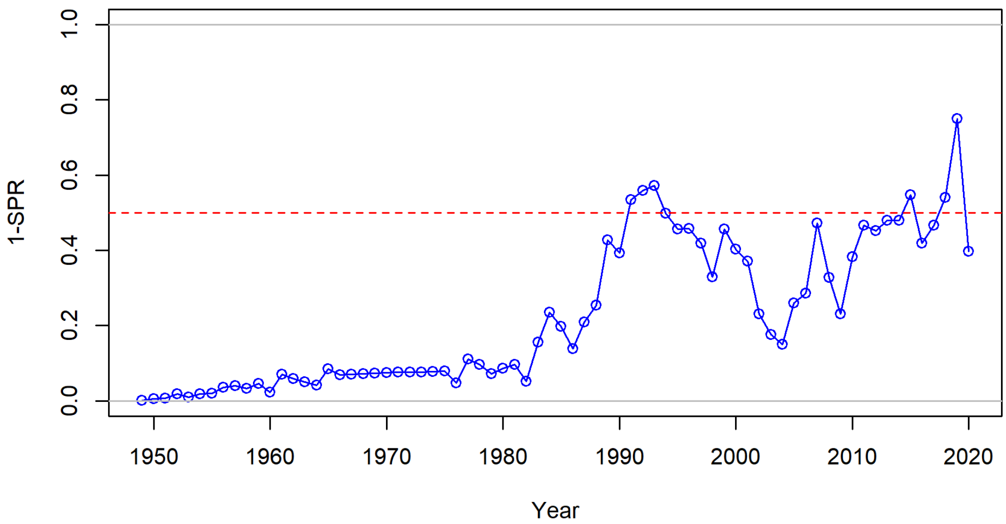

Figure vi: Estimated 1 - relative spawning ratio (SPR) by year for the base model. The management target is plotted as a red horizontal line and values above this reflect harvest in excess of the proxy harvest rate.

Ecosystem Considerations

This stock assessment does not explicitly incorporate trophic interactions, habitat factors or environmental factors into the assessment model. More predation, diet and habitat work, and mechanistic linkages to environmental conditions would be needed to incorporate these elements into the stock assessment.

Reference Points

The 2021 spawning biomass relative to unfished equilibrium spawning biomass is above the management target of 40 percent of unfished spawning biomass. The relative biomass and the ratio of the estimated SPR to the management target ($SPR_{50\%}$) across all model years are shown in Figure vii where warmer colors (red) represent early years and colder colors (blue) represent recent years. There have been periods where fishing intensity has been higher than the target fishing intensity based on $SPR_{50\%}$, but the stock status has always been above the target. Figure viii shows the equilibrium curve based on a steepness value fixed at 0.72 with vertical dashed lines to indicate the estimate of fraction unfished at the start of 2021 (current) and the estimated management targets calculated based on the relative target biomass (B target), the SPR target, and the maximum sustainable yield (MSY).

Reference points were calculated using the estimated selectivity and catch distribution for the recreational fleet in the most recent year of the model, 2020 (Table 12). Sustainable total yield, removals, using a $SPR_{50\%}$ is 0.771 mt. The spawning output equivalent to 40 percent of the unfished spawning biomass ($SB_{40\%}$) calculated using the SPR target ($SPR_{50\%}$) was 1.225 meggs. Recent removals have been close to the point estimate of potential long-term yields calculated using an $SPR_{50\%}$ reference point and the population size has been fluctuating, but consistently above the target over the past few years.

Table v: Summary of reference points and management quantities, including estimates of the 95 percent intervals.

	Estimate	Lower Interval	Upper Interval
Unfished Spawning Output	2.75	0.74	4.75
Unfished Age 3+ Biomass (mt)	36.04	8.49	63.60
Unfished Recruitment (R0)	2.48	0.00	5.46
Spawning Output (2021)	1.55	0.00	4.00
Fraction Unfished (2021)	0.56	0.06	1.07
Reference Points Based SB40%			
Proxy Spawning Output SB40%	1.10	0.30	1.90
SPR Resulting in SB40%	0.46	0.46	0.46
Exploitation Rate Resulting in SB40%	0.06	0.04	0.08
Yield with SPR Based On SB40% (mt)	0.81	0.05	1.57
Reference Points Based on SPR Proxy for MSY			
Proxy Spawning Output (SPR50)	1.23	0.33	2.12

Table v: Summary of reference points and management quantities, including estimates of the 95 percent intervals. *(continued)*

	Estimate	Lower Interval	Upper Interval
SPR50	0.50		
Exploitation Rate Corresponding to SPR50	0.05	0.04	0.07
Yield with SPR50 at SB SPR (mt)	0.77	0.05	1.49
Reference Points Based on Estimated MSY Values			
Spawning Output at MSY (SB MSY)	0.75	0.28	1.22
SPR MSY	0.34	0.32	0.37
Exploitation Rate Corresponding to SPR MSY	0.09	0.06	0.13
MSY (mt)	0.87	0.05	1.70

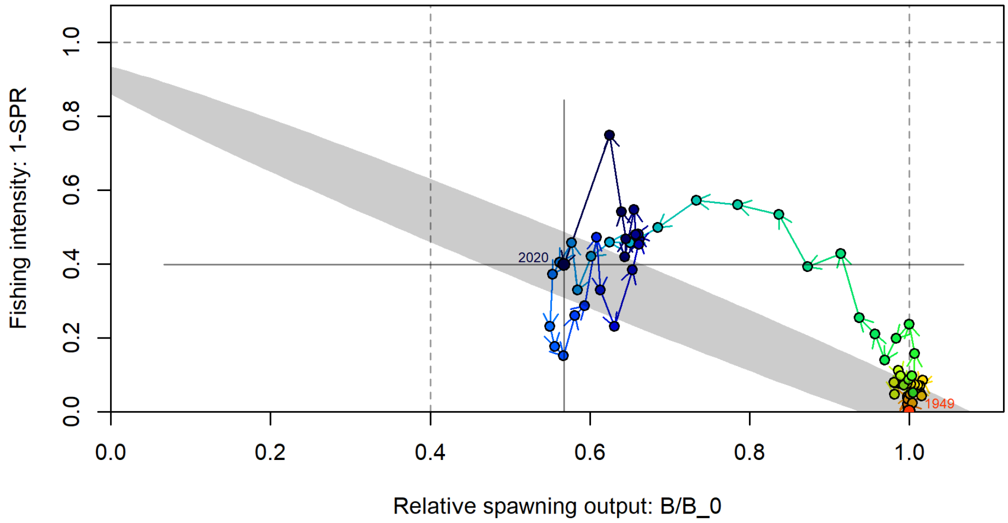

Figure vii: Phase plot of estimated 1-SPR versus fraction unfished for the base model.

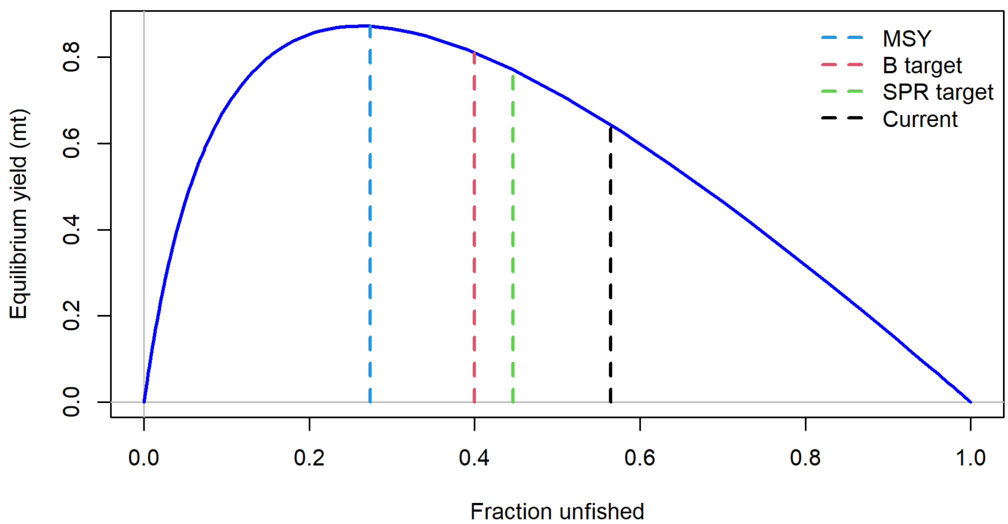

Figure viii: Equilibrium yield curve for the base case model. Values are based on the 2020 fishery selectivities and with steepness fixed at 0.80.

Management Performance

Exploitation on vermilion rockfish increased starting around the mid-1980s and reaching relatively high levels in the early 1990s. Since that time, catch has mostly fluctuated between 100 and 700 fish a year, with a peak of >1200 fish in 2019. The last ten years of the vermilion component acceptable biological catch (ABC) and annual catch limit (ACL) (which are equivalent) of the Minor Shelf Rockfish North Complex are by definition set below the overfishing limit (OFL) (Table vi). The Washington contribution to the component ACL has not exceeded the colletitve vermilion rockfish component ACL for this complex, and is a very minor portion of the overall coastwide take of vermilion rockfish.

Table vi: The OFL, ABC, ACL, landings, and the estimated total mortality in metric tons.

Year	OFL	ABC	ACL	Landings	Est. Total Mortality
2011	11.1	5.6	5.6	1.01	1.01
2012	11.1	5.6	5.6	0.95	0.95
2013	9.7	8.1	8.1	1.05	1.05
2014	9.7	8.1	8.1	1.04	1.04
2015	9.7	8.1	8.1	1.32	1.32
2016	9.7	8.1	8.1	0.82	0.82
2017	9.7	8.1	8.1	0.97	0.97
2018	9.7	8.1	8.1	1.24	1.24
2019	9.7	8.1	8.1	2.60	2.60
2020	9.7	8.1	8.1	0.66	0.66

Unresolved Problems and Major Uncertainties

This assessment, while having multiple years of length and age data, has low samples sizes for each data source. The growth estimates seem reasonable and do not tend to add a large amount of variability to the model outputs, the major source of uncertainty stems from the uncertainty in natural mortality. This uncertainy seems larger than even among model uncertainty in the treatments of data or alternative model specifications. The ability to decrease the uncertainty in this parameter would then bring attention back to alternative model specifications.

The structure of this model is simple– one non-target fleet and stationary productivity and selectivity with recruitment deviations allowing to add non-deterministic changes to the population, yet there is an observable retrospective pattern. This would suggest some sort of bias in the data and/or model misspecification. The limited data and simple model structure makes the latter difficult to explore. It may also be inherent in the fact that this is a small population sensitive to perturbations. Attention to this restrospective pattern should be maintained in future assessments as data increases.

The large ageing error seen in the Committee of Age Reading Experts (CARE) exchange was untenable for use in a reference model, but should be revisited with further exchanges to figure out why the Washington Depatment of Fish and Wildlife ageing was such an outlier to the other laboratories. Further work on the age and growth of vermilion rockfish in Washington would help improve the ageing error and overall growth estimates.

Historical catches are roughly estimated, though little additional information is available to improve this estimate. While historical catches are very uncertain, the levels are so small compared to the population that is makes little difference in model results, though remains an area of uncertainty.

Scientific Uncertainty

The model-estimated uncertainty around the 2021 spawning biomass was $\sigma = 0.71$ and the uncertainty around the OFL was $\sigma = 0.76$. This is likely an underestimate of overall uncertainty because of the necessity to fix some parameters such as steepness, as well as a lack of explicit incorporation of model structural uncertainty.

Harvest Projections and Decision Table

A ten year (2023-2032) projection of the reference model with removals in 2021 and 2022 provided by the Groundfish Management Team for each fleet under the category 2 (sigma=1.0) time-varying buffer using $P^* = 0.45$ and 40-10 ABC control rule is provided in Table 13.

Table vii: Projections of potential OFLs (mt), ABCs (mt), the buffer (ABC = buffer x OFL), estimated spawning biomass, and fraction unfished. The North of 40°10'N OFL and ABC for 2021 and 2022 are included for comparison.

Year	OFL 40°10'N	ACL 40°10'N	Predicted OFL	ABC Catch	Buffer	Spawning Output	Fraction Unfished
2021	9.7	8.1	0.94	2.69	1.00	1.55	0.56
2022	9.7	8.1	0.84	3.26	1.00	1.37	0.50
2023	-	-	0.70	0.61	0.87	1.15	0.42
2024	-	-	0.70	0.61	0.87	1.14	0.42
2025	-	-	0.70	0.61	0.86	1.13	0.41
2026	-	-	0.71	0.61	0.85	1.13	0.42
2027	-	-	0.72	0.61	0.84	1.13	0.42
2028	-	-	0.73	0.61	0.83	1.13	0.43
2029	-	-	0.74	0.62	0.83	1.14	0.43
2030	-	-	0.75	0.62	0.82	1.14	0.43
2031	-	-	0.76	0.62	0.81	1.15	0.44
2032	-	-	0.77	0.62	0.80	1.16	0.44

The decision table (Table viii) was constructed using female and male natural mortality to define the low and high states of nature. The multi-parameter likelihood profile was used to find the low (Female M = 0.07092; Male M= 0.06525) and high (Female M = 0.08527; Male M = 0.07845) female and male natural mortality values that produce -log likeliehood values +0.66 units from the reference -log likelihood value. These correspond to the 12.5% and 87.5% quantiles (standard quantiles used in west coast decision tables). The catch rows in the table were based on three proposed catch streams:

1. P* = 0.45, sigma = 1.0
2. P* = 0.40, sigma = 1.0
3. An equilibrium catch based on the F_{MSY} proxy using SPR = 0.5

Vermilion rockfish stock assessments in California had category 2 designations with more data, but also more uncertainty given the mixed species (sunset and vermilion rockfishes) nature of the fishery. It is believed only vermilion are caught in Washington state, but the category 2 sigma = 1.0 used in the decision tables was based on high model uncertainty.

Catch is modelled as numbers in the assessment, which necessitated conversion of biomass based estimates into numbers for projections. This means that while biomass-based catch streams within each row are static, the numbers associated with those biomass estimates change across the states of nature given age and length structures of varying among states of nature. This requires conversion of biomass to numbers in every year of all low and high states of nature in order to maintain the biomass estimates at expected values. A check was made for each scenario of the decision table to make sure inputted removals in numbers match the expected removals in biomass.

The fixed values for 2021-2022 are very high catches compared to the historical take of vermilion rockfish in Washington state. This has a notable effect on the stock size and status of the low M state of nature. While the reference and high state of nature runs keeps the population near or well above the target stock status for all catch streams, the low state of nature falls well below the overfished limit. The catch streams also show a large drop in catch after the fixed values of 2021-2022, highlighting how each catch control rule will lead to large reductions in future vermilion rockfish catch.

Table viii: Decision table summary of 10 year projections beginning in 2023 for alternative states of nature based on an axis of uncertainty about female and male natural mortality for the reference model. Columns range over low (12.5 quantile), mid (reference model), and high states (87.5 quantile) of nature and rows range over different catch level assumptions. Values in italics indicate years where the stock size prevented the full catch removals.

			Female M = 0.067; Male =0.069		Female M = 0.084; Male =0.086		Female M = 0.099; Male =0.100	
	Year	Catch	Spawning Output	Fraction Unfished	Spawning Output	Fraction Unfished	Spawning Output	Fraction Unfished
	2021	2.69	0.68	0.31	1.55	0.56	3.62	0.81
	2022	3.26	0.50	0.23	1.38	0.50	3.44	0.77
	2023	0.62	0.28	0.13	1.16	0.42	3.21	0.72
	2024	0.61	0.26	0.12	1.15	0.42	3.20	0.72
	2025	0.61	0.25	0.11	1.15	0.42	3.19	0.72
P*=0.45	2026	0.61	0.24	0.11	1.15	0.42	3.18	0.72
sigma=1.0	2027	0.61	0.24	0.11	1.16	0.42	3.18	0.72
	2028	0.62	0.24	0.11	1.17	0.43	3.19	0.72
	2029	0.62	0.24	0.11	1.18	0.43	3.20	0.72
	2030	0.62	0.24	0.11	1.20	0.44	3.21	0.72
	2031	0.63	0.24	0.11	1.21	0.44	3.23	0.73
	2032	0.63	0.24	0.11	1.23	0.45	3.24	0.73
	2021	2.69	0.68	0.31	1.55	0.56	3.62	0.81
	2022	3.26	0.50	0.23	1.38	0.50	3.44	0.77
	2023	0.54	0.28	0.13	1.16	0.42	3.21	0.72
	2024	0.53	0.27	0.12	1.16	0.42	3.20	0.72
	2025	0.53	0.26	0.12	1.16	0.42	3.20	0.72
P*=0.4	2026	0.53	0.26	0.12	1.17	0.43	3.20	0.72
sigma=1.0	2027	0.53	0.26	0.12	1.18	0.43	3.21	0.72
	2028	0.53	0.27	0.12	1.20	0.44	3.22	0.72
	2029	0.53	0.27	0.12	1.22	0.44	3.24	0.73
	2030	0.53	0.28	0.13	1.24	0.45	3.26	0.73
	2031	0.52	0.29	0.13	1.26	0.46	3.28	0.74
	2032	0.52	0.30	0.13	1.28	0.47	3.30	0.74
	2021	2.69	0.68	0.31	1.55	0.56	3.62	0.81
	2022	3.26	0.50	0.22	1.38	0.50	3.44	0.77
	2023	0.77	0.28	0.13	1.15	0.42	3.21	0.72
	2024	0.77	0.25	0.11	1.14	0.41	3.18	0.72
FMSY proxy	2025	0.77	0.23	0.10	1.12	0.41	3.16	0.71
SPR=0.5	2026	0.77	0.21	0.09	1.11	0.40	3.15	0.71
	2027	0.77	0.19	0.09	1.11	0.40	3.14	0.71
	2028	0.77	0.18	0.08	1.11	0.40	3.13	0.70
	2029	0.77	0.17	0.08	1.11	0.40	3.13	0.70
	2030	0.77	0.16	0.07	1.11	0.40	3.13	0.70
	2031	0.77	0.15	0.07	1.12	0.41	3.14	0.71
	2032	0.77	0.14	0.06	1.12	0.41	3.15	0.71

Research and Data Needs

1. Resolution in stock structure. The Washington population of vermilion rockfish seems to have a large degree of separation from the core population and even the main population found in Oregon. Washington state has begun sampling tissue from landed vermilion rockfish in order to add more resolution to the genetic relatedness among vermilion found in U.S. waters.

2. The degree of ageing error between otoliths read in the Washington Department of Fish and Wildlife agein lab and others in the CARE exchange highlights the need for further exchanges to determine why these differences exist, as they do not within the WDFW ageing lab, nor among the reads from the other labs. The CARE exchange has high value in general to further our ability to understand the inherent variability of reading ageing structures, and should be strongly supported.

3. The life history parameters are all assumed constant through time. This assumption of stationarity is one of convenience and parsimony. Any insight into the changing of life history values or differing productivity regimes could help refine these assumptions.

4. Natural mortality proved the source of greatest uncertainty in the model. While empirical methods can help define priors for natural mortality, good sampling of age structure or direct measures (e.g., tagging) are preferred. While the small size and rare occurrence of vermilion rockfish off Washington state makes these direct methods a challenge to do, improved data collection may help with natural mortality estimation and reduce model uncertainty.

5. Sample sizes for biological data are small in this assessment, so increases in samples could help reduce model uncertainty. The practicality of this suggestion is questionable as the limited number of vermilion rockfish encountered makes it difficult to increase sample sizes.

6. A fishery-independent index of abundance would be a welcome inclusion in this assessment. Again, such a rarely encountered fish may be hard to monitor via an index of abundance, but the possibility of a nearshore/shallow shelf survey is welcome.

7. The large uncertainty estimated in this stock assessment was limited given the asymptotic, symmetric variance estimation from the maximum likelihood estimation method. While a Bayesian model was considered and even explored for this model, it was not included due to challenges in implementation and lack of enough time to achieve a converged model. Continuted development of Bayesian approaches to characterizing uncertainty are strongly encouraged.

8. Ensemble modelling may be another potential tool to incorporate model uncertainty beyond within model variance estimation that should be considered.

9. Fishery selectivity continues to be challenging to represent, and are key parameters in the model. Blocks in selectivity and whether there are *apriori* reasons to expect any dome-shaped selectivity deserve continued thought, though again it is especially challenging given the rarity of occurrence and non-target nature of vermilion rockfish.

1 Introduction

1.1 Basic Information

This assessment reports the status of vermilion rockfish (*Sebastes miniatus*) off the waters of Washington state using data through 2020. Vermilion rockfish range from Prince William Sound, Alaska, to central Baja California at depths of 6 m to 436 m (Love, Yoklavich, and Thorsteinson 2002). They are most commonly found from southern Oregon to Punta Baja, Mexico (Hyde and Vetter 2009) at depths of 50 m to 150 m (Hyde and Vetter 2009). Hyde et al. [-hyde_cryptic_2008] describe an additional cryptic species related to vermilion rockfish, the sunset rockfish (*Sebastes crocotulus*). They note that vermilion rockfish reside in shallower depths (<100 m) compared to sunset rockfish. Sunset rockfish tend to be more southerly, and have not been reported in Oregon, so this assessment focuses only on vermilion rockfish. Adult vermilion rockfish tend to cluster on high relief rocky outcrops (Love, Yoklavich, and Thorsteinson 2002) and kelp forests (Hyde and Vetter 2009). North of Point Conception, some adults are shallower, living in caves and cracks (Love, Yoklavich, and Thorsteinson 2002). Vermilion rockfish have shown high site fidelity (Robert W. Hannah and Rankin 2011 (only tagged 1 vermilion rockfish); Lea, McAllister, and VenTresca 1999), and low average larval dispersal distance (Hyde and Vetter 2009). Lowe et al. (2009) suggested vermilion rockfish have a lower site fidelity than previously believed, but they acknowledged that their observations of movements to different depths may have been due to the reality of a shallower species and a deeper species.

The stock designation of Washington waters as a management unit was based on the observation that most of the habitat and take of vermilion rockfish off Washington was in the very northern portion of the Washington coast, while most vermilion rockfish in Oregon are taken off southern Oregon (Figure 1). Ninety-seven percent of vermilion rockfish catch comes from the northern portion of Washington and ninety percent of the total mortality in Oregon is from the southern part of the state (south of Pt. Arago; Figure 2). This large area of separation, low movement of larvae and adults, and the biogeographic barriers of the Columbia River outfall and lack of rocky habitat in southern Washington all support separate Washington-Oregon management units. Given the extreme range of vermilion in Washington waters, they are not expected much north into Canadian waters, nor are they found with any regularity in Puget Sound.

1.2 Life History

The approximate average lifespan for vermilion rockfish rockfish is 60 years, with females living longer and growing larger than their male counterparts. 50% are mature at 5 years and about 37 cm, with males probably maturing at shorter lengths than females (Love, Yoklavich, and Thorsteinson 2002).

Vermilion rockfish are viviparous, and release 63,000 to 2,600,000 eggs per season. In southern California, vermilion rockfish larvae are released between July and March. In central and northern California, this release occurs in September, December, and April-June (Love, Yoklavich, and Thorsteinson 2002). In Oregon, fertilized females with ripe ovaries are encountered from April to October (Robert W. Hannah and Kautzi 2012), with larval release sometime during and after that period. Larval release in fall and winter is not common among other rockfish species. Hyde and Vetter (2009) suggest that low larval dispersal may be due to weak poleward flow of nearshore waters corresponding with peak vermilion rockfish larval release.

Young-of-the-year (YOY) vermilion rockfish settle out of the plankton during two recruitment periods per year, first from February to April and a second from August to October, and settlement has been observed in May off southern California (Love, Yoklavich, and Thorsteinson 2002). There is no information on YOY settlement in Oregon. Larvae measure about 4.3 mm. Both young-of-the-year vermilion and sunset rockfish are mottled brown with areas of black, and older juveniles turn a mottled orange or red color (Love et al. 2012). Juvenile fish are found individually from 6 m to 36 m, living near sand and structures. After two months, juveniles travel deeper and live on low relief rocky outcrops and other structures (Love, Yoklavich, and Thorsteinson 2002).

Adult vermilion rockfish predominantly eat smaller fish, though sometimes they pursue euphausiids and other various macroplankton (Phillips 1964). Love (2002) noted their diet to include octopus, salps, shrimps, and pelagic red crabs.

1.3 Ecosystem Considerations

This stock assessment does not explicitly incorporate trophic interactions, habitat factors or environmental factors into the assessment model, but a brief description of likely or potential ecosystem considerations are provided below.

Vermilion rockfish feed on a wide range of both pelagic and benthic prey items, including forage fish species such as anchovies and mesopelagic fishes, squid, krill and octopus, as well as sporadically abundant pelagic organisms such as pyrosomes, salps and pelagic red crabs (Phillips 1964; Love, Yoklavich, and Thorsteinson 2002). Interestingly, other rockfishes (either juvenile or adult stages) have not been documented as prey for vermilion rockfish as they have for other larger *Sebastes* species (e.g., cowcod, bocaccio and yelloweye rockfish). Pelagic and benthic juvenile vermilion rockfish are likely preyed upon by the same wide range of predators that prey on juveniles and adults of other rockfish species, including seabirds, piscivorous fishes, and marine mammals.

As with most other rockfish and groundfish in the California Current, recruitment, or cohort (year-class) strength appears to be highly variable for the vermilion rockfish, with only a modest apparent relationship to spawning output. Oceanographic and ecosystem factors are widely recognized to be key drivers of recruitment variability for most species of groundfish, as well as most elements of California Current food webs. Empirical estimates of recruitment from pelagic juvenile rockfish surveys have been used to inform incoming year class strength for some of these stocks, however vermilion and sunset rockfish are rarely encountered in these surveys. Specifically, only 47 of nearly 300,000 total juvenile *Sebastes* encountered in juvenile surveys since 2001 were identified as vermilion or sunset rockfish (Field et al. 2021). Previous studies have demonstrated that large-scale oceanographic drivers, such as the relative transport of subarctic waters (typically indicated by relative sea level) tend to relate to a substantial fraction of overall groundfish recruitment trends and ecosystem productivity Schroeder et al. (2019). Although it is feasible that ecosystem factors, the results of pre-recruit surveys for co-occurring species, or the results of other groundfish assessments might ultimately be used to forecast recruitment for more data-limited stocks such as vermilion rockfish, as suggested by (James T. Thorson and Ward 2014), such approaches would require more development and evaluation. Consequently, environmental factors are not explicitly considered in this assessment.

1.4 Historical and Current Fishery Information

Off the coast of Washington state, vermilion rockfish is primarily caught in the recreational/sport fishery with very little mortality from commercial fishing (Table 1). Vermilion rockfish has been a target of recreational fishing as early as 1949 with catches varying each year from about 100 fish to over 1000 fish (in numbers) since then.

Vermilion rockfish has not been targeted by commercial fisheries in Washington waters. Washington closed state waters to commercial fixed gears in 1995 and to trawling in 1999. Off Washington, the depths preferred by vermilion rockfish are predominantly found within state waters. Washington state closed its waters in response to the development of the live-fish fishery in California and Oregon, and took preemptive action in 1999 to prevent the fishery from developing by prohibiting the landing of live-fish. At the time, rockfish were believed to be low productivity and could not support both commercial and recreational fishing pressure in state waters. There are four treaty tribes that fish under separate rules and are not subject to the state water closure; however, to date, no vermilion rockfish have been observed within a species composition sample at any tribal commercial offloads. Vermilion rockfish are landed in the Nearshore Rockfish group, a mixed-species market category. Species composition samples were taken from sampled landings and proportions of vermilion rockfish reported in the Nearshore market category would be estimated by port, quarter, gear, and year. In 2020, COVID-19 closures of tribal lands prevented samplers from accessing all commercial catch.

Examination of the WCGOP data set, 2002-2019, also shows that commercial catches of vermilion rockfish are rare off Washington. In the individual fishing quota program–which began in 2011 and where coverage of discards is effectively 100 percent–there has been only one vermilion rockfish catch event observed. The boat is recorded as having caught 400 lbs of vermilion rockfish and as departing from and returning to a port in Oregon. The catch from that boat was recorded as having been retained and therefore would have been recorded on an Oregon fish ticket. WCGOP has also covered the Limited Entry Sablefish fishery since 2002. Observers recorded three catch events of vermilion rockfish off Washington in 2002 totalling 25 lbs. Observer coverage in that fishery sector in 2002 was over 20%. Since 2002 observer coverage in that sector has ranged from 9%-52%. Only one other catch of vermilion rockfish has been recorded off Washington. The non-trawl Rockfish Conservation Area off of

Washington extends from shore to 100 fathoms and excludes the sector from core vermilion rockfish habitats. WCGOP also covered the ocean pink trawl fishery in Washington since 2010 at coverage levels of 9%-19% and has recorded a single vermilion rockfish catch event off Washington of 2 lbs.

The primary region where vermilion rockfish is most common is the Washington coast occurs in the northern most regions. These areas have rocky habitat that rockfish species such as vermilion rockfish rockfish are associated with in comparison to the southern coast of Washington which consists primarily of soft and sandy substrate. The stock off the Washington coast was assessed as a separate stock from other populations off the West Coast based on three factors: 1) suspected limited flow of fish between Washington and Oregon given the substrate separation, 2) the different exploitation patterns within Washington waters compared to Oregon and California, and 3) the quantity of length data in Washington compared to other areas.

1.5 Summary of Management History and Performance

Vermilion rockfish is managed by the Pacific Fishery Management Council (PFMC) as a part of the Shelf Rockfish North and Shelf Rockfish South complexes. The North and South areas are split at 40°10’ North latitude off the California. The complex is managed based on a complex level overfishing limit (OFL) and annual catch limit (ACL). The OFL and ACL values for the complex are determined by summing the species specific OFLs and ACLs managed within the complex. Removals for species within the Rockfish complex are managed and tracked against the complex total OFL and ACL, rather than on a species by species basis. The OFL and ACLs for vermilion rockfish North of 40°10’ Lat. N. management area and the total removals are shown in Table 2. There are no state-specific allocations of this complex and so removals are evaluated at the regional level (North of 40°10’).

2 Data and Model Inputs

A description of each data source is provided below (Figure 3).

2.1 Fishery-Dependent Data

2.1.1 Recreational

2.1.1.1 Removals

Annual catches (Table 1) from the recreational fishery (1967, 1979-2020) were obtained from historical reports, and landings from 1990-2020 were obtained from the Washington

Department of Fish and Wildlife (WDFW) Ocean Sampling Program (OSP) and Puget Sound Baseline Sampling Program. Puget Sound is not included in this assessment, as that is Washington State waters exclusively, but vermilion rockfish is a relatively rare species in the Puget Sound and Salish Sea. Previous to 1979, the ratio of vermilion to black rockfish for years both were recorded was used to build a predictive linear relationship to fill in years of missing vermilion catches (Figure 4). This choice was made to leverage the historical black rockfish catch reconstruction performed by Cope et al. (2016), as black rockfish are the most common rockfish caught in Washington, and has an overlapping presence with vermilion. The predictive ratio was used to find landed values (in numbers of fish) between 1968 and 1979, and resulted in zero landings in 1949, thus defining the start year of the model. Because the relationship is highly variable, the mininum and maximum ratios were taken and multiplied by black rockfish catch in the missing vermilion years to construct alternative catch histories. These two catch histories built with extremes in the vermilion:black rockfish ratio were explored in sensitivity models runs. Lastly, the 1967 value was deemed unrealistc, as it was an order of magnitude higher than reported landings in the 1970s, and it came from a sample of two caught fish from Area 2, which is not expected to contain much vermilion habitat. The extreme expansion of two fish into such a large landings estimate from an area not known for vermilion catch was too suspect to support, so it also became part of the linear interpolaton process described above. A model run with the original 1967 value showed very little sensitivity to this value.

Discard estimates are not available prior to 2002. Based on a discard to retained catch relationship from 2002 to 2020, we estimated historical discards. Discard mortality by depth was applied to post-2001 discards estimate. Prior to 2002, a 32% mortality rate is applied to discarded fish. The sum of retained and dead released vermilion rockfish made up the total removal (in numbers) from the recreational fishery.

2.1.1.2 Lengths

Length compositions for the recreational fleet were available in 1977, 1978, 1980 - 1983, 1986, and then each year from 1993 - 2020 (Table 3; Figure 5). The number of length observations by year were quite variable ranging between 1 and 266 samples per year. Only years with samples sizes >10 were used in the model, as years with low sample sizes can sometimes destabalize models while adding little information. The size of sexed and unsexed fish observed by the recreational fleet were between 22 and 77 cm. The mean length observed by year was much smaller in early years, but averaged around 45 cm since 1996.

2.1.1.3 Ages

Numbers of collected age structures vary from 3 to 150 per year since 1998, with the majority of the collected age structures coming from 2015 - 2020 (Table 4). No age structures were taken in 2003. The mean minimum age for all years is 6 with the mean max age being 44. The average age across all years is 16. The oldest aged fish in Washington waters is 68 in 1998, but there have been several aged over 50.

2.2 Fishery-Independent Data

2.2.1 Washington Nearshore Survey

Data from Washington Department of Fish and Wildlife's Nearshore Rockfish Survey were analyzed to see if an index could be generated, or if additional length data could be added to this assessment. The current data are not extremely robust and the methods have not been reviewed by the SSC, so these data were not used in this assessment. This survey could prove a useful data set in the future once the method review has been completed.

Trawl surveys often used in west coast groundfish assessments (e.g., Triennial survey, Alaskan slope survey and the West Coast Groundfish Bottom Trawl Survey) do collect fishery-independent abundance and biological data off the Washington coast. However, those surveys are not designed to cover vermilion rockfish habitat in Washington, and vermilion are rarely if ever encountered. Indices of abundance were therefore not calculated from these surveys.

2.3 Biological Parameters

2.3.1 Growth (Length-at-Age)

The length-at-age was estimated for female and male vermilion rockfish using data from collections sampling the recreational fishery off the coast of Washington from years 2004-2020 (Table 4. Inital attempts of estimating the growth parameters provided very small t_0 values (<-6). Values for t_0 were then fixed to the Oregon values and L_∞ and k were estimated:

$$\text{Females } L_\infty = 57.1 \text{ cm; } k = 0.093\text{; } t_0 = \text{-2.78}$$
$$\text{Males } L_\infty = 54.2 \text{ cm; } k = 0.109\text{; } t_0 = \text{-1.96}$$

The estimated VBGF parameters provided initial values for the estimation of growth in the model, as all age and length data are included in the model. Sex-specific growth curves (i.e., females are larger than males) estimated by the model without fixing to the Oregon t_0 values are presented in Figure 7. Sensitivities to the treatment of growth parameters (fixed or estimated) are explored through sensitivity analyses.

2.3.2 Ageing Precision and Bias

Counting ages from ageing structures in long-lived temparate fishes is challenging. Ages derived from these structures can be hard to reproduce within and between readers (i.e., imprecision), and may not contain the true age (i.e., bias). Stock assessment outputs can be affected by bias and imprecision in ageing, thus it is important to quantify and integrate this source of variability when fitting age data in assessments. In Stock Synthesis, this is done by including ageing error matrices that include the mean age (row 1) and standard deviation in age (row 2). Ageing bias is implemented when the inputted mean age deviates from the expected middle age for any given age bin (e.g., 1.75 inputted versus 1.5 being the true age); ageing imprecision is given as the standard deviation for each age bin (row 2).

An ageing error matrix for the recreational fishery samples were calculated using within reader comparisons (n = 861). An additional ageing error matrix was constructed from the Committee of Age Reading Experts (CARE) otolith exchange, where an exchange of 50 individuals was done among WDFW, ODFW, SWFSC, and NWFSC. The WDFW internal read ageing error matrix was used in the reference model, with the CARE comparison explored in a sensitivity model run.

Estimation of ageing error matrices used the approach of Punt et al. (2008) and release 1.1.0 of the R package nwfscAgeingError (J. T. Thorson, Stewart, and Punt 2012). The ageing error matrix offers a way to calculate both bias and imprecision in age reads. In this analysis, Reader 1, the primary reader of the ages used in the stock assessment, is always considered unbiased, but may be imprecise. Several model configurations are available for exploration based on either the functional form (e.g., constant CV, curvilinear standard deviation, or curvilinear CV) of the bias in reader 2 or in the precision of the readers. Model selection uses AIC corrected for small sample size (AICc), which converges to AIC when sample sizes are large. Bayesian Information Criterion (BIC) was also considered when selecting a final model. Table 5 provides model selection results. Bias can be added to the primary reader when inputting the ageing error into Stock Synthesis if additional information informs the bias, but this was not done in this assessment.

The WDFW intralab comparison supported imprecision with a curvilinear standard deviation for the recreational fishery. The CARE comparison was also curvelinear, but on the coefficient of variation, with huge ageing error imprecision as age increases. The functional forms for each matrix are given in Figure 8.

2.3.3 Natural Mortality

Natural mortality was not directly measured, so life-history based empirical relationships were used. The Natural Mortality Tool (NMT; https://github.com/shcaba/Natural-Mortality-Tool), a Shiny-based graphical user interface allowing for the application of a variety of natural mortality estimators based on measures such as longevity, size, age and growth, and maturity, was used to obtain estimates of natural mortality. The NMT currently provides 22 options, including the Hamel (2015) method, which is a corrected form of the Then et al. (2015) functional regression model and is a commonly applied method for west coast groundfish. The NMT also allows for the construction of a natural mortality prior weighted across methods by the user.

We assumed the age of 54 years to represent the practical longevity (i.e., 90% of the commonly seen maximum age of 60) for both females and males, though the absolute oldest age in

Washington was >60 years. In the larger biomass, higher sampled area of California, ages 80+ were even encountered. Empirical M estimators using the von Bertalanffy growth parameters were also considered, but they produced unreasonably high estimates (2-3 times higher than the longevity estimates). This is likely explained by the fact that vermilion rockfish have protracted longevity at L_{∞}. Additionally, the FishLife (James T. Thorson, Munch, et al. 2017) estimate was included, though, given the source of FishLife data is FishBase, there is a good chance the estimates of M are also from methods using longevity, though the actual source of longevity in FishLife was unknown. The final composite M distribution (Figure 11) is based on 4 empirical estimators, and result in a median value of 0.1. We assume a lognormal distribution with a standard deviation of 0.438 (Hamel (2015)) for the purposes of the prior used to estimate M. This creates a wide prior to allow the data in the model to also influence the final estimated value of M. We also explore sensitivity to these assumptions of natural mortality through likelihood profiling.

2.3.4 Maturation and Fecundity

Maturity-at-length is borrowed from the work of Hannah and Kautzi (2012) which is based on samples from Oregon and estimated the 50 percent size-at-maturity of 39.4 cm, though the slope of the maturity curve was not provided. Looking at the maturity curve in Hannah and Kautzi (2012), and length at 95% maturity was assumed at 48 cm, resulting in a slope of -0.34. Maturity was assumed to stay asymptotic for larger fish (Figure 9) as no functional maturity estimate was available (Head, Cope, and Wulfing 2020).

The fecundity-at-length was provided by E.J. Dick (SWFSC), and is consistent with what is being used for the California vermilion assessments. The fecundity relationship for vermilion rockfish was estimated equal to Fec=4.32e-07$L^{3.55}$ in millions of eggs where L is length in cm. Fecundity-at-length is shown in Figure 10.

2.3.5 Length-Weight Relationship

The length(cm)-weight(kg) relationship for vermilion rockfish was estimated outside the model using all Washington state biological data available from the recreational fishery, the only sex-specific information on length and weight available (Figure 12). The estimated length-weight relationship for female fish was W=1.36e-05$L^{3.1}$ and males at W=2.38e-05$L^{2.96}$.

2.3.6 Sex Ratio

No information on the sex ratio at birth was available so it was assumed to be 50:50.

2.3.7 Steepness

The Thorson-Dorn rockfish prior (developed for use West Coast rockfish assessments) conducted by James Thorson (personal communication, NWFSC, NOAA) and reviewed and endorsed by the Scientific and Statistical Committee (SSC) in 2017, has been a primary source of information on steepness for rockfishes. This approach, however, was subsequently rejected for future analysis in 2019 when the new meta-analysis resulted in a mean value of approximately 0.95. In the absense of a new method for generating a prior for steepness the default approach reverts to the previously endorsed method, the 2017 prior for steepness (h; beta distribution with μ=0.72 and σ=0.15) is retained.

3 Assessment Model

3.1 Summary of Previous Assessments

Vermilion rockfish in Washington has not been previously assessed in full, so this is the first benchmark for this management unit. Depletion-based Stock Reduction Analysis (DBSRA) assuming 40% depletion in 2009 was used to set annual catch limits (ACLs) for vermilion rockfish since 2010 (Dick and MacCall 2010). The total vermilion rockfish OFL in 2011 was 319.5 mt. The mean sustainable yield for the northern portion was estimated to be 11.1 mt, just 3.5% of the total OFL. Most of this allocation would be expected to come from California, as the population of vermilion rockfish continues to be smaller north of California.

3.1.1 Modelling Platform

Stock Synthesis version 3.30.16 was used as the statistical catch-at-age modelling framework. The SS-DL tool (https://github.com/shcaba/SS-DL-tool) was used for model exploration, likelihood profiling, and sensitivity analyses. The companion R package r4ss (version 1.38.0) along with R version 4.0.5 were used to investigate and plot model fits.

3.1.2 Bridging Analysis

No analysis bridging the DBSRA model and Stock Synthesis model was conducted given the significant differences (e.g., DBSRA is provided the relative stock status value) between the methods. It is well documented already that SS can mimic DBSRA approaches (Jason M. Cope 2013).

3.2 Model Structure and Assumptions

Stock Synthesis is an age-structured modelling framework that allows for the integration of removal histories, length and age compositions in one model. The Washington vermilion rockfish model assessment assumes one removal fleet (a recreational fishery, thus negligible commerical removals) with removals (in 1000s of fish) beginning in 1949. Selectivity for the fleet were specified using the double normal parameterization within SS where selectivity was fixed to be asymptotic with the ascending slope and size of maximum selectivity parameters estimated. Life history parameters are sex-specific, with one growth type, and assumed stationary. Recruitment assumes a Beverton-Holt stock-recruit relationship and recruitment deviations are estimated.

3.2.1 Estimated and Fixed Parameters

Natural mortality (M) and all growth parameters (L_∞, k, t_0, CV at t_0, and CV at L_∞) are estimated, as is the two selectivity parameters, the log of the initial recruitment ($logR_0$), and recruitment deviations. Length at maturity, fecundity-weight, and length-weight relationshop, steepness (h) and recruitment variance were all fixed. Sensitivity scenarios and likelihood profiles were used to explore uncertainty in the values of the natural mortality and growth parameters. When estimating parameters, the prior for natural mortality was assumed lognormal with a standard deviation of 0.438 (based on the prior developed using the Natural Mortality Tool (see Biology section for more details)); growth parameters were estimated with no priors.

3.2.2 Data Weighting

Initial sample sizes for the Washington recreational length and age samples were based on the number of fish sampled. The method of Francis (2011, equation TA1.8) was then used to balance the length and conditional age-at-length composition data among other inputs and likelihood components. The Francis method treats mean length and age as indices, with effective sample size defining the variance around the mean. If the variability around the mean does not encompass model predictions, the data should be down-weighted until predictions fit within the intervals. This method accounts for correlation in the data (i.e., the multinomial distribution), but can be sensitive to years that are outliers, as the amount of down-weighting is applied to all years within a data source, and are not year-specific. Sensitivities were performed examining different data-weighting treatments: 1) the Dirichlet-Multinomial approach (James T. Thorson, Johnson, et al. 2017), 2) the McAllister-Ianelli Harmonic Mean approach (McAllister and Ianelli 1997), or 3) no data-weighting of lengths.

3.3 Model Selection and Evaluation

The base assessment model for Washington vermilion rockfish was developed to balance parsimony and realism, and the goal was to estimate a spawning output trajectory and realtive stock status for the population of vermilion rockfish in state and federal waters off Washington. The model contains many assumptions to achieve parsimony and uses different data types and sources to estimate reality. A series of investigative model runs were done to achieve the final base model. These include considerations of model structure, data and parameter treatment, estimation phasing, and jittered starting values to achieve a converged and balanced model that provides sensible parameter estimates and derived quantities.

3.4 Summary of Previous Assessments and Reviews

There are no previous assessments for the Washington vermilion rockfish management unit, thus no summary of previous assessments or reviews.

3.4.1 History of Modeling Approaches

The previous treatment of vermilion rockfish that contained the area of Washington was the application of DBSRA in order to determine OFLs, and was not a model to provide estimates of stock status.

3.4.2 Most Recent STAR Panel and SSC Recommendations (not required for an update assessment)

There are no recent STAR or SSC recommendations regarding Washington vermilion rockfish.

3.5 Reference Model Diagnostics and Results

3.5.1 Model Convergence and Acceptability

While there is no definitive measure of model convergence, several measures are routinely applied. These criteria include a low maximum gradient (9.25736×10^{-5}), inversion of the Hessian (passed), reasonable parameter values (passed), and acceptable fits to data (passed).

An extra effort was given to ensure the model did not rest on a local likelihood minimum. This was done by starting the minimization process from dispersed parameter values away from the maximum likelihood estimates to determine if the approach found a better model fit (i.e., minimum negative log-likelihood value). Starting parameters used a jitter shift value of 0.001. This was repeated 100 times with 30 out of 100 runs returned to the reference model likelihood (Figure 14). A better fit, lower negative log-likelihood model was not found in any of the remaining 91 runs. The model did not experience convergence issues when provided reasonable starting values. Through the jittering and likelihood profiles, the present reference model represents the best fit to the data given the assumptions made.

3.5.1.1 Fits to the Data

3.5.1.1.1 Lengths

Fits to the length data are examined based on the Pearson residuals-at-length, the annual mean lengths, and aggregated length composition data. Model fits to the annual length composition are shown in Appendix A. Lengths are generally sampled better after year 2014, but the overall samples are generally low (e.g., only 3 years have a total sample size > 100).

Pearson residuals of fits to the length data are generally low with no distinct pattern of misfitting despite lower sample sizes (Figure 15). Fits to the mean lengths, assuming Francis data-weighting, show decreasing female and males lengths after 1999, with a very small increase in mean lengths after 2008, though the overall trend is fairly stable (Figure 16). Aggregate fits over years are shown in Figure 17. Given the small sample sizes, the model fits the aggregate lengths adequately.

3.5.1.1.2 Conditional Age at Length

Fits to the conditioanl age at length data are examined based on the age-at-length Pearson residuals, the annual mean ages, and mean age at length by year for the recreational fleet samples. The maximum size of the Pearson residuals was large (maximum = 15.95; Appendix B), though these large residuals were not common. Most of the residuals were small and unnoteworthy and demonstrate the expected shape of the growth curve. As with the lengths, the mean age by year decreased after 1999 then leveled off and gradually increased from 2009 onward (Figure 18). Mean ages were generally between 15 year and 20 years old. Fits to the mean ages by length bins show acceptable fits consistent with model expectations Appendix C.

3.5.2 Reference Model Outputs

3.5.2.1 Parameter Estimates

A total of fifteen primary parameters were estimated, along with seventy-two recruitment deviations. The reference model parameter estimates along with asymptotic standard errors are shown in Table 6 and the likelihood components are shown in Table 7. Estimates of derived reference points and approximate 95 percent asymptotic confidence intervals are provided in Table 12. The low sample sizes, but consistent signal in the data sets, along with so many estimated parameters allows the model to incorporate a large amount of variance in the derived outputs.

The natural mortality for females and males was estimated at 0.085 and 0.087 yr^{-1}, respectively. These values are below the mean prior value, but not unreasonable given the corresponding longevities would be between 62 and 64 years old and the sampled maximum age of 68 came from a fished population.

The estimates of sex-specific growth parameters showed some differences from the externally estimated starting values (Table 6 and Figure 7). While L_∞ was similar to the external estimates, the model estimated k for female and male fish were lower than the values estimated externally (0.093 for females and 0.103 yr^{-1} for males). The majority of female and male vermilion rockfish growth occurs at younger ages, reaching near maximum length by age 30-40, depending upon sex, with female vermilion rockfish reaching larger maximum lengths (Figure 7). The t_0 values (female = -2.779; male = -1.961 were more biologically reasonable than the external estimates using the Washington data.

The estimated logistic selectivity curve for the recreational fishery look plausible (i.e., as a model convergence check for realism, the selectivity curve is not overtly outrageous; Figure 19). Length at 50% selectivity (44.267 cm) was between the length at 50% (39.4 cm) and 95% maturity (48 cm).

The time series of estimated recruitments and annual recruitment deviations are shown in Figures 23 and 24. Recruitment strengths were generally low; years with the highest recruitment deviations were estimated to have occurred in 1995, 1996, 1999, 2000, 2006, and 2011. All recruitment deviations after 2011 are negative. The variance check on the recruitment deviations indicates weakly informed recruitments. Recruitment deviations after 2015 are relatively uninformed with estimated deviations near zero where recruitment is estimated primarily based on the spawner-recruit curve (Figure 26). The recruitment bias adjustment applied within the model across years is shown in Figure 27.

3.5.2.2 Population Trajectory

The predicted spawning output (in millions of eggs) is provided in Table 8 and plotted in Figure 20. Estimated spawning output shows a large decline starting after 1980, with a leveling off of the population after 2000. This tracks the time period of major removals, though removals have stayed somewhat elevated in recent years, bouyed by small but positive recruitments. A decline since 2019 is due to the largest catch on record in 2019 (almost twice the previous largest catch). The estimate of total biomass over time, which tracks that of spawning output, is shown in Figure 21. Numbers of age-0 individuals indcate years of above average recruitment (Figure 23).

Median relative spawning output has never declined below the management target ($SB_{40\%}$), and has hovered near 60% for the past 20 years (Figure 22). The relative stock status at the start of 2021 is estimated to be well above the rockfish relative biomass target of 0.4 (0.56). Uncertainty intervals are extremely wide (from near extinct to unfished) given the number of estimated parameters, indicating an overall weakness in the data to firmly inform relative stock status.

3.6 Uncertainty exploration

3.6.1 Sensitivity Analyses

Sensitivity analyses were conducted to evaluate model sensitivity to alternative data treatment and model specifications.

3.6.1.1 Data treatment sensitivities

Data treatments explored were as follows:

- Data removal (fixed life history, no recruitment estimation)
  1. Fishery length data only (no catches; L)
  2. Catch and lengths only (CL)
  3. Catch and lengths only with Francis weighting (CL_Fr)
  4. Catch, lengths, and ages with Francis weighting (CLA_fixed)
  5. Catch, length, and age with Francis weighting and estimated recruitment (CLA_fixed_recs)
- Data weighting
  6. Dirichlet data-weighting
  7. McAllister-Ianelli data weighting
  8. No data-weighting
- Catch histories
  9. Catch using original 1967 catches
  10. Minimum historical (1949-1977) catch series
  11. Maximum historical (1949-1977) catch series
- Length treatment
  12. Use option sex = 3 to maintain sex ratio in commercial data
- Ageing error
  13. Using ageing error from CARE exchange

Likelihood values and estimates of key parameters and derived quantities from each sensitivity are available in Table 9. Derived quantities relative to the reference model are provided in Figure 29. Time series of spawning output and relative spawning output are shown in Figures 30 and 31.

The deterministic length-based model without catches and with fixed life history values view the stock scale and status to be below that of the reference model and near the target reference point. Bringing in the length data returns the model back to reference levels, but introducing age data with out without recruitment while still fixing life history parameters significantly raises the stock scale and relative stock staus above the reference model. The other data treatments, including data weighting options, did very little to change the results from the reference model, except the choice of using the CARE ageing error matrix. The matrix ageing error was so extreme, it caused the model to not converge.

3.6.1.2 Model specification sensitivities

Model specifications looked at the estimation of indiviual and combinations of life history parameters, the estimation of recruitment, and the treatment of fecundity and selectivity. All scenarios match the reference model specifications in all other aspects unless otherwise stated.

- Life history estimation

  1. Fix all life history parameters

  - Fix natural mortality (M)

    2. Fix M
    3. Fix M, k, t_0, and CVs
    4. Fix M, t_0, and CVs
    5. Fix M and CVs
    6. Fix female M and growth parameters
    7. Fix male M and growth parameters

  - Fix growth parameters

    8. Fix all growth parameters
    9. Fix L_∞ and CVs
    10. Fix k and CVs
    11. Fix CVs
    12. 5 growth platoons instead of one

  - Recruitment estimation and variability (σ_R). All years are estimated with bias correction applied.

    13. No recruitment estimation
    14. $\sigma_R = 0.45$

15. $\sigma_R = 0.75$

- Miscellaneous

16. Fecundity proportional to weight
17. Estimate dome-shaped selectivity
18. Estimate Lorenzen age-based mortality

Likelihood values and estimates of key parameters and derived quantities from each sensitivity are available in Tables 10 and 11. Derived quantities relative to the reference model are provided in Figure 32. Time series of spawning output and relative spawning output are shown in Figures 33 and 34.

Fixing all life history parameters significantly increases the scale and status of the stock. Fixing M to the higher prior mean value raised both the beginning and ending stock scale and overall ending year relative stock status, except when estimating L_∞ (at an un reasonably low value of 52 and 49 cm for females and males respectively) that maintained the intial stock scale near the reference level, but increased the current stock status.

Model results were less sensitive to fixing growth parameters. Fixing all growth parameters had the largest relative affect of raising both scale and stock status, as it caused M to be lower, but wasn't a dramatic departure from the reference model. The initial growth values have small L_∞ values compared to estimates, so it is expected all scenarios with small L_∞ values will reflect a higher stock status and scale. The choice of invoking 5 growth types resulted is less current spawning output and relative stock scale. This makes sense if more of the population is available to the fishery given the fishery selectivity curve. Further investigation of the affects of life history values are provided in the likelihood profiles (next section).

Model results were not sensitive to the following model specifications: not estimating recruitment, changing the value of recruitment variability, treatment of fecundity, dome-shaped selectivity estimation (very little dome-shaped selectivity was indicated), or implementing age-based natural mortality through the Lorenzen model.

Overall, there were few model specification sensitivity scenarios that caused the population to drop below the reference model estimate of stock status, and nothing that dropped it below the target reference point. When stock scale differed, it was mostly due to the treatment of natural mortality or small L_∞ values and current stock size was often what changed the most. From these results, it is likely most of the model uncertainty is due to M, and that while the variance is forced to be normally distributed in the asymptotic form, it is mostly on the upper side of both scale and status compared to the reference model.

3.6.2 Likelihood Profiles

Likelihood profiles were conducted for $ln(R_0)$, steepness (h), female and male natural mortality (M) values separately and varying together, female and male maximum length (L_∞), female and male growth coefficient (k), female and male variability of size at maximum age. In addition, joint profiles over L_∞ and k (that maintains a correlation structure -0.92 between the parameters consistent with the model calculation of that correlation) were done for females and males separately. Female and male natural mortality was also covaried based on the offset in values from the reference model. Likelihood profiles were conducted by fixing the featured parameter(s) at specific values across a range of values and estimating the remaining parameters. A likelihood profile offers insight into model information on a given parameter or parameter pairing, while providing an additional way to describe uncertainty in the parameter by indentifying the range of parameters within 1.96 likelihood units of the refrence model.

The $ln(R_0)$ profiles show strong support for the maximum likelhood value of 0.91 (Figure 35). Population size expectedly increases as $ln(R_0)$ increases, with the increase in current biomass happening quicker than initial biomass, thus relative stock status increase towards unfished at high $ln(R_0)$ values. This is explained by the harvest rate decreasing because the removal history is fixed and becomes relatively smaller compared to the overall biomass. All data sets were mostly consistent in the information content in the profile, though the length data contained the least amount of information on $ln(R_0)$.

The steepness profile showed no information content for this parameter (Figure 36). Despite this lack of information on steepness, model output show little senstivity to stock scale (SB_0 and SB_2021) or relative stock status. The recruitment likelihood was the biggest driver of steepness towards a value of 1 (Figure 36).

Natural mortality profiles for females (Figure 37) and males (Figure 38) are consistent with each other and show a wide range of M values for females and males supported by the data. Possible values for M are both above and below the mean of the prior (0.1) for both sexes. The combined profile that varies female and male M based on the reference offset together at the same changing value behave similarly to the individual likelihood profiles (Figure 39). Scale and relative stock status are affected by this parameter, with the current spawning output being affected more than initial biomass. This is particularly true as M gets larger, creating much higher biomass and higher relative stock status. The uncertainty in the relative stock status ranges from 0.06 to 0.12, very consistent with the asymptotic uncertainty intervals for this value from in reference model, though the likelihood profiles demonstrate the true assymetry in the uncertainty in derived quantities. Comparing the assymetric range of relative stock status estimates in the profiled values (Figure 40) to the normally distributed uncertainty envelope in the reference model (Figure 22), one can clearly see the overestimation of the low end of relative stock status when assuming a normal error distribution. The length, then age data provided the strongest data signal for natural mortality and were generally consistent with each other.

Female and male growth profiles show good signals in the data to estimate L_∞ (Figures 41 and 45), k (Figures 42 and 46), and length CV at maximum age (Figures 44 and 48).

L_∞ had the largest variance of the growth parameters. Lengths and ages are the primary data informing growth parameters with consistent signals. A more realistic profile that maintains the negative correlation bewtween L_∞ and k showing show similar behavior as the two separate profiles (Figure 43). The range of growth parameters explored in the likelihood profiles showed little affect on either scale or stock status; female k and length CV at maximum age had the relatively biggest effect on scale for growth parameters, but overall these were small. These profiles support the conculsion that the main source of uncertainty in the model is the treatment of natural mortality.

3.6.3 Retrospective Analysis

A ten-year retrospective analysis was conducted by running the model and sequentially removing one year of data up through minus 10 years. Retrospective spawning output (Figure 49) and relatives stock status (Figure 50) estimates were generally within the large confidence intervals of the reference model. There does seem to be a retrospective pattern with removal of years 1-6 leading to smaller biomass and lower stock scale, though this is result changes with the exclusion of years 7-10. All results maintained the population above the stock status target reference point changed in all years.

3.7 Management

3.7.1 Reference Points

Reference points were calculated using the estimated fishery selectivity and removals in the most recent year of the model (2020, Table 12). Sustainable total yields were 0.77 mt when using an $SPR_{50\%}$ reference harvest rate. The spawning output equivalent to 40 percent of the unfished spawning output ($SB_{40\%}$) was 1.23 meggs.

The 2021 spawning output relative to unfished equilibrium spawning output is above the vermilion rockfish relative biomass target of 40 percent (Figure 22). The fishing intensity, $1 - SPR$, of recent years was near or above the harvest rate limit ($SPR_{50\%}$) in the early 1990s and late 2010s. Recent years also show near target fishing levels (Table 8 and Figure 51). Table 12 shows the full suite of estimated reference points for the base model and Figure 53 shows the equilibrium curve based on a steepness value fixed at 0.72.

3.7.2 Unresolved Problems and Major Uncertainties

This assessment, while having multiple years of length and age data, has low annual samples sizes for each data source. The growth estimates seem reasonable and do not tend to add a large amount of variability to the model outputs, as the major source of uncertainty stems from the uncertainty in natural mortality. This uncertainty seems larger than even among model uncertainty in the treatments of data or alternative model specifications. The ability to decrease the uncertainty in this parameter would then bring attention back to alternative model specifications.

The structure of this model is simple– one non-target fleet with stationary productivity and selectivity and stochastic recruitment allowing non-deterministic changes to the population, yet there is an observable retrospective pattern. This would suggest some sort of bias in the data and/or model misspecification. The limited data and simple models structure makes the latter difficult to explore. It may also be inherent in the fact that this is a small population sensitive to perturbations. Attention to this restrospective pattern should be maintained in future assessments as data increases.

The large ageing error seen in the CARE exchange was untenable for use in a reference model, but should be revisited with further exchanges to figure out why the Washington state ageing was such an outlier to the other laboratories. Further work on the age and growth of vermilion rockfish in Washington would help improve the ageing error and overall growth estimates, and the collection of small individuals would be particularly helpful.

The historical catch history is roughly estimated, though little additional information is avialble to improve this estimate. While this history is very uncertain, the catch level is so small compared to the contemporary catch and overall population that it makes little difference in model results, but remains an area of uncertainty.

3.7.3 Harvest Projections and Decision Tables

A ten year (2023-2032) projection of the reference model with removals in 2021 and 2022 provided by the Groundfish Management Team for each fleet under the category 2 (sigma=1.0) time-varying buffer using $P^* = 0.45$ and 40-10 ABC control rule is provided in Table 13.

The decision table (Table 14) was constructed using female and male natural mortality to define the low and high states of nature. The multi-parameter likelihood profile was used to find the low (Female M = 0.07092; Male M= 0.06525) and high (Female M = 0.08527; Male M = 0.07845) female and male natural mortality values that produce -log likeliehood values +0.66 units from the reference -log likelihood value. These correspond to the 12.5% and 87.5% quantiles (standard quantiles used in west coast decision tables). The catch rows in the table were based on three proposed catch streams: 1. P* = 0.45, sigma = 0.5 2. P* = 0.40, sigma = 0.5 3. An equilibrium catch based on the F_{MSY} proxy using SPR = 1.0

Catch is modelled as numbers in the assessment, which necessitated conversion of biomass based estimates into numbers for projections. This means that while biomass-based catch streams within each row are static, the numbers associated with those biomass estimates change across the states of nature given age and length structures of varying among states of nature. This requires conversion of biomass to numbers in every year of all low and high states of nature in order to maintain the biomass estimates at expected values. A check was made for each scenario of the decision table to make sure inputted removals in numbers match the expected removals in biomass.

The fixed values for 2021-2022 are very high catches compared to the historical take of vermilion rockfish in Washington state. This has a notable effect on the stock size and status of the low M state of nature. While the reference and high state of nature runs keeps the population near or well above the target stock status for all catch streams, the low state of nature falls well below the overfished limit. The catch streams also show a large drop in catch after the fixed values of 2021-2022, highlighting how each catch control rule will lead to large reductions in future vermilion catch.

3.7.4 Evaluation of Scientific Uncertainty

The estimated uncertainty in the base model around the 2021 spawning output is $\sigma = 0.71$ and the uncertainty in the base model around the 2021 OFL is $\sigma = 0.76$. The large uncertainty aligns with a category 2 level of uncertainty, though the estimated model uncertainty was less than the category 2 groundfish data moderate assessment default value of $\sigma = 1.0$. The reasons for designating this a category 2 stock (high estimated model uncertainty) was different than the category 2 California models that were based heavily on the mix of sunset and vermilion rockfishes.

3.8 Research and Data Needs

1. Resolution in stock structure. The Washington population of vermilion rockfish seems to have a large degree of separation from the core population and even the main population found in Oregon. Washington state has begun sampling tissue from landed vermilion rockfish in order to add more resolution to the genetic relatedness among vermilion found in U.S. waters.
2. The degree of ageing error between otoliths read in the Washington Department of Fish and Wildlife agein lab and others in the CARE exchange highlights the need for further exchanges to determine why these differences exist, as they do not within the WDFW ageing lab, nor among the reads from the other labs. The CARE exchange has high value in general to further our ability to understand the inherent variability of reading ageing structures, and should be strongly supported.
3. The life history parameters are all assumed constant through time. This assumption of stationarity is one of convenience and parsimony. Any insight into the changing of life history values or differing productivity regimes could help refine these assumptions.
4. Natural mortality proved the source of greatest uncertainty in the model. While empirical methods can help define priors for natural mortality, good sampling of age structure or direct measures (e.g., tagging) are preferred. While the small size and

rare occurrence of vermilion rockfish off Washington state makes these direct methods a challenge to do, improved data collection may help with natural mortality estimation and reduce model uncertainty.

5. Sample sizes for biological data are small in this assessment, so increases in samples could help reduce model uncertainty. The practicality of this suggestion is questionable as the limited number of vermilion rockfish encountered makes it difficult to increase sample sizes.
6. A fishery-independent index of abundance would be a welcome inclusion in this assessment. Again, such a rarely encountered fish may be hard to monitor via an index of abundance, but the possibility of a nearshore/shallow shelf survey is welcome.
7. The large uncertainty estimated in this stock assessment was limited given the asymptotic, symmetric variance estimation from the maximum likelihood estimation method. While a Bayesian model was considered and even explored for this model, it was not included due to challenges in implementation and lack of enough time to achieve a converged model. Continuted development of Bayesian approaches to characterizing uncertainty are strongly encouraged.
8. Ensemble modelling may be another potential tool to incorporate model uncertainty beyond within model variance estimation that should be considered.
9. Fishery selectivity continues to be challenging to represent, and are key parameters in the model. Blocks in selectivity and whether there are *apriori* reasons to expect any dome-shaped selectivity deserve continued thought, though again it is especially challenging given the rarity of occurrence and non-target nature of vermilion rockfish.

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6 Tables

Table 1: Total catches (in 1000s of fish and metric tons), including discards for the recreational fleet by year

Year	Numbers in 1000s	Mt
1949	0.00	0.00
1950	0.00	0.01
1951	0.01	0.01
1952	0.01	0.03
1953	0.01	0.02
1954	0.02	0.04
1955	0.02	0.04
1956	0.03	0.07
1957	0.04	0.08
1958	0.03	0.06
1959	0.04	0.09
1960	0.02	0.04
1961	0.06	0.14
1962	0.05	0.12
1963	0.04	0.10
1964	0.04	0.08
1965	0.08	0.17
1966	0.06	0.14
1967	0.06	0.14
1968	0.06	0.14
1969	0.06	0.14
1970	0.06	0.14
1971	0.07	0.15
1972	0.07	0.15
1973	0.07	0.15
1974	0.07	0.15
1975	0.07	0.15
1976	0.04	0.09
1977	0.10	0.22

Table 1: Total catches (in 1000s of fish and metric tons), including discards for the recreational fleet by year *(continued)*

Year	Numbers in 1000s	Mt
1978	0.09	0.19
1979	0.07	0.14
1980	0.08	0.17
1981	0.09	0.20
1982	0.05	0.10
1983	0.15	0.33
1984	0.24	0.54
1985	0.19	0.43
1986	0.12	0.28
1987	0.19	0.44
1988	0.24	0.54
1989	0.48	1.09
1990	0.40	0.91
1991	0.63	1.45
1992	0.65	1.49
1993	0.64	1.45
1994	0.47	1.06
1995	0.39	0.87
1996	0.38	0.84
1997	0.33	0.71
1998	0.23	0.49
1999	0.38	0.79
2000	0.31	0.64
2001	0.27	0.56
2002	0.15	0.30
2003	0.11	0.22
2004	0.10	0.19
2005	0.19	0.38
2006	0.23	0.44
2007	0.50	0.95

Table 1: Total catches (in 1000s of fish and metric tons), including discards for the recreational fleet by year *(continued)*

Year	Numbers in 1000s	Mt
2008	0.29	0.56
2009	0.19	0.36
2010	0.38	0.74
2011	0.52	1.01
2012	0.49	0.95
2013	0.54	1.05
2014	0.53	1.04
2015	0.67	1.32
2016	0.42	0.82
2017	0.49	0.97
2018	0.62	1.24
2019	1.29	2.60
2020	0.32	0.66

Table 2: The OFL and ACL for vermilion rockfish as a component of the Minor Shelf Rockfish North complex and the total estimated removals of vermilion rockfish in Washington (including estimated discards). There is no Washington-specific allocation of Minor Shelf Rockfish North.

Year	OFL	ACL	Total Removals
2011	11.1	5.6	9.1
2012	11.1	5.6	11.9
2013	9.7	8.1	9.7
2014	9.7	8.1	6.2
2015	9.7	8.1	6.1
2016	9.7	8.1	5.7
2017	9.7	8.1	12.1
2018	9.7	8.1	12.3
2019	9.7	8.1	13.1
2020	9.7	8.1	11.3

Table 3: Length samples for Washington vermilion rockfish by sex.

Year	Unknown	Female	Male
1977	1	0	0
1978	5	0	0
1980	4	0	0
1981	5	0	0
1982	2	0	0
1983	1	0	0
1986	3	0	0
1995	2	0	0
1996	0	0	0
1997	0	0	0
1998	0	6	7
1999	0	18	21
2000	0	4	8
2001	0	4	4
2002	0	2	1
2003	0	1	0
2004	0	8	7
2005	0	11	16
2006	0	15	12
2007	0	14	22
2008	0	14	14
2009	0	4	5
2010	0	2	1
2011	0	7	4
2012	0	10	7
2013	0	3	2
2014	2	29	29
2015	8	76	46
2016	3	45	43
2017	1	35	46

Table 3: Length samples for Washington vermilion rockfish by sex. *(continued)*

Year	Unknown	Female	Male
2018	2	45	55
2019	1	87	72
2020	0	10	8

Table 4: Recreational age samples for Washington vermilion rockfish.

Year	Unknown	Female	Male	Total
1998	0	6	7	13
1999	0	18	16	34
2000	0	4	8	12
2001	0	2	2	4
2002	0	2	1	3
2004	0	7	4	11
2005	0	10	13	23
2006	0	13	12	25
2007	0	14	21	35
2008	0	14	14	28
2009	0	4	5	9
2010	0	2	1	3
2011	0	7	4	11
2012	0	9	7	16
2013	0	3	2	5
2014	2	29	27	58
2015	7	75	45	127
2016	3	44	40	87
2017	1	35	45	81
2018	2	35	48	85
2019	1	80	69	150

Table 5: Ageing error models and resultant model selection (AICc) values for 9 models of bias and precision explored for each lab used in the vermilion rockfish assessments. Bolded text indicates the chosen model. Model codes: 0= unbiased; 1 = Constant CV; 2 = Curvilinear (SD for precision); 3= Curvilinear CV. CARE comparison has 4 readers

	Reader 1		**Reader 2 (to 4)**		**Reader Model selection**			
Model	Bias	Precision	Bias	Precision	AICc	ΔAICc	BIC	ΔBIC
WDFW								
1	0	1	0	1	9076	37	9234	18
2	0	2	0	2	9058	19	9223	7
3	0	3	0	3	9080	42	9246	30
4	0	1	1	1	9068	30	9238	21
5	0	2	1	2	9074	35	9250	34
6	**0**	**3**	**1**	**3**	**9**039	**1**	**9**216	**0**
7	0	1	2	1	9074	35	9251	34
8	0	2	2	2	9038	0	9223	6
9	0	3	2	3	9039	1	9224	7
CARE								
1	0	1	0	1	1064	79	1178	52
2	0	2	0	2	1063	78	1181	55
3	0	3	0	3	1071	86	1189	63
4	0	1	1	1	999	15	1130	4
5	0	2	1	2	994	9	1128	2
6	0	3	1	3	1024	39	1158	31
7	0	1	2	1	1014	29	1153	26
8	**0**	**2**	**2**	**2**	**9**85	**0**	**1**126	**0**
9	0	3	2	3	1001	16	1142	16

Table 6: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values not estimated), status (indicates if parameters are near bounds), and prior type information (mean and SD).

Parameter	Value	Phase	Bounds	Status	Prior (Exp.Val, SD)
NatM p 1 Fem GP 1	0.085	3	OK	0.0129347	Log Norm (-2.30259, 0.438)
L at Amin Fem GP 1	1.968	3	OK	3.70137	None
L at Amax Fem GP 1	57.106	3	OK	1.01762	None
VonBert K Fem GP 1	0.093	3	OK	0.00850602	None
CV young Fem GP 1	0.090	3	OK	0.0265344	None
CV old Fem GP 1	0.053	3	OK	0.00664901	None
Wtlen 1 Fem GP 1	0.000	-99	-	-	None
Wtlen 2 Fem GP 1	3.100	-99	-	-	None
Mat50% Fem GP 1	39.400	-99	-	-	None
Mat slope Fem GP 1	-0.342	-99	-	-	None
Eggs scalar Fem GP 1	0.000	-3	-	-	None
Eggs exp len Fem GP 1	3.548	-3	-	-	None
NatM p 1 Mal GP 1	0.087	3	OK	0.0134205	Log Norm (-2.30259, 0.438)
L at Amin Mal GP 1	-2.671	3	OK	4.76078	None
L at Amax Mal GP 1	54.240	3	OK	0.687875	None
VonBert K Mal GP 1	0.109	3	OK	0.00906197	None
CV young Mal GP 1	0.149	3	OK	0.0402358	None
CV old Mal GP 1	0.037	3	LO	0.00760099	None
Wtlen 1 Mal GP 1	0.000	-99	-	-	None
Wtlen 2 Mal GP 1	2.960	-99	-	-	None
CohortGrowDev	1.000	-1	-	-	None
FracFemale GP 1	0.500	-99	-	-	None
SR LN(R0)	0.908	1	OK	0.612927	None
SR BH steep	0.720	-1	-	-	None
SR sigmaR	0.600	-6	-	-	None
SR regime	0.000	-99	-	-	None
SR autocorr	0.000	-99	-	-	None
Early InitAge 1	0.060	3	act	0.615948	dev (NA, NA)
Main RecrDev 1949	0.107	1	act	0.627134	dev (NA, NA)

Table 6: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values not estimated), status (indicates if parameters are near bounds), and prior type information (mean and SD). *(continued)*

Parameter	Value	Phase	Bounds	Status	Prior (Exp.Val, SD)
Main RecrDev 1950	0.163	1	act	0.643499	dev (NA, NA)
Main RecrDev 1951	0.202	1	act	0.655332	dev (NA, NA)
Main RecrDev 1952	0.205	1	act	0.656279	dev (NA, NA)
Main RecrDev 1953	0.169	1	act	0.644486	dev (NA, NA)
Main RecrDev 1954	0.109	1	act	0.625618	dev (NA, NA)
Main RecrDev 1955	0.046	1	act	0.606875	dev (NA, NA)
Main RecrDev 1956	-0.008	1	act	0.591989	dev (NA, NA)
Main RecrDev 1957	-0.047	1	act	0.581748	dev (NA, NA)
Main RecrDev 1958	-0.069	1	act	0.575812	dev (NA, NA)
Main RecrDev 1959	-0.075	1	act	0.573543	dev (NA, NA)
Main RecrDev 1960	-0.068	1	act	0.574223	dev (NA, NA)
Main RecrDev 1961	-0.054	1	act	0.577099	dev (NA, NA)
Main RecrDev 1962	-0.034	1	act	0.581387	dev (NA, NA)
Main RecrDev 1963	-0.011	1	act	0.586455	dev (NA, NA)
Main RecrDev 1964	0.015	1	act	0.592478	dev (NA, NA)
Main RecrDev 1965	0.046	1	act	0.600844	dev (NA, NA)
Main RecrDev 1966	0.091	1	act	0.613803	dev (NA, NA)
Main RecrDev 1967	0.157	1	act	0.633468	dev (NA, NA)
Main RecrDev 1968	0.243	1	act	0.659115	dev (NA, NA)
Main RecrDev 1969	0.318	1	act	0.680349	dev (NA, NA)
Main RecrDev 1970	0.318	1	act	0.677163	dev (NA, NA)
Main RecrDev 1971	0.228	1	act	0.647798	dev (NA, NA)
Main RecrDev 1972	0.112	1	act	0.613624	dev (NA, NA)
Main RecrDev 1973	0.024	1	act	0.589122	dev (NA, NA)
Main RecrDev 1974	-0.022	1	act	0.574495	dev (NA, NA)
Main RecrDev 1975	-0.046	1	act	0.563294	dev (NA, NA)
Main RecrDev 1976	-0.089	1	act	0.550197	dev (NA, NA)
Main RecrDev 1977	-0.178	1	act	0.534298	dev (NA, NA)
Main RecrDev 1978	-0.284	1	act	0.517754	dev (NA, NA)

Table 6: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values not estimated), status (indicates if parameters are near bounds), and prior type information (mean and SD). *(continued)*

Parameter	Value	Phase	Bounds	Status	Prior (Exp.Val, SD)
Main RecrDev 1979	-0.353	1	act	0.506578	dev (NA, NA)
Main RecrDev 1980	-0.358	1	act	0.503724	dev (NA, NA)
Main RecrDev 1981	-0.302	1	act	0.507597	dev (NA, NA)
Main RecrDev 1982	-0.231	1	act	0.512859	dev (NA, NA)
Main RecrDev 1983	-0.221	1	act	0.510556	dev (NA, NA)
Main RecrDev 1984	-0.284	1	act	0.503176	dev (NA, NA)
Main RecrDev 1985	-0.330	1	act	0.496782	dev (NA, NA)
Main RecrDev 1986	-0.296	1	act	0.496976	dev (NA, NA)
Main RecrDev 1987	-0.216	1	act	0.497525	dev (NA, NA)
Main RecrDev 1988	-0.150	1	act	0.498427	dev (NA, NA)
Main RecrDev 1989	-0.125	1	act	0.490802	dev (NA, NA)
Main RecrDev 1990	-0.171	1	act	0.4933	dev (NA, NA)
Main RecrDev 1991	-0.051	1	act	0.487257	dev (NA, NA)
Main RecrDev 1992	0.001	1	act	0.479754	dev (NA, NA)
Main RecrDev 1993	-0.192	1	act	0.499607	dev (NA, NA)
Main RecrDev 1994	-0.007	1	act	0.511951	dev (NA, NA)
Main RecrDev 1995	0.219	1	act	0.536386	dev (NA, NA)
Main RecrDev 1996	0.316	1	act	0.4807	dev (NA, NA)
Main RecrDev 1997	-0.143	1	act	0.503712	dev (NA, NA)
Main RecrDev 1998	-0.049	1	act	0.527827	dev (NA, NA)
Main RecrDev 1999	0.520	1	act	0.557418	dev (NA, NA)
Main RecrDev 2000	1.370	1	act	0.332128	dev (NA, NA)
Main RecrDev 2001	0.015	1	act	0.551525	dev (NA, NA)
Main RecrDev 2002	-0.499	1	act	0.458786	dev (NA, NA)
Main RecrDev 2003	-0.429	1	act	0.457812	dev (NA, NA)
Main RecrDev 2004	-0.054	1	act	0.458839	dev (NA, NA)
Main RecrDev 2005	0.137	1	act	0.53278	dev (NA, NA)
Main RecrDev 2006	0.993	1	act	0.360992	dev (NA, NA)
Main RecrDev 2007	0.468	1	act	0.451916	dev (NA, NA)

Table 6: List of parameters used in the base model, including estimated values and standard deviations (SD), bounds (minimum and maximum), estimation phase (negative values not estimated), status (indicates if parameters are near bounds), and prior type information (mean and SD). *(continued)*

Parameter	Value	Phase	Bounds	Status	Prior (Exp.Val, SD)
Main RecrDev 2008	-0.300	1	act	0.476217	dev (NA, NA)
Main RecrDev 2009	-0.275	1	act	0.459163	dev (NA, NA)
Main RecrDev 2010	0.176	1	act	0.450055	dev (NA, NA)
Main RecrDev 2011	0.299	1	act	0.435636	dev (NA, NA)
Main RecrDev 2012	-0.232	1	act	0.496431	dev (NA, NA)
Main RecrDev 2013	-0.330	1	act	0.504523	dev (NA, NA)
Main RecrDev 2014	-0.237	1	act	0.53221	dev (NA, NA)
Main RecrDev 2015	-0.177	1	act	0.561097	dev (NA, NA)
Main RecrDev 2016	-0.044	1	act	0.585831	dev (NA, NA)
Main RecrDev 2017	-0.008	1	act	0.595358	dev (NA, NA)
Main RecrDev 2018	-0.007	1	act	0.595827	dev (NA, NA)
Main RecrDev 2019	-0.007	1	act	0.595838	dev (NA, NA)
Main RecrDev 2020	-0.007	1	act	0.595838	dev (NA, NA)
ForeRecr 2021	0.000	4	act	0.6	dev (NA, NA)
ForeRecr 2022	0.000	4	act	0.6	dev (NA, NA)
InitF seas 1 flt 1Fishery	0.000	-1	-	-	None
Size DblN peak Fishery(1)	44.267	2	OK	1.65543	None
Size DblN top logit Fishery(1)	15.000	-1	-	-	None
Size DblN ascend se Fishery(1)	4.142	2	OK	0.308667	None
Size DblN descend se Fishery(1)	-15.000	-1	-	-	None
Size DblN start logit Fishery(1)	-15.000	-2	-	-	None
Size DblN end logit Fishery(1)	15.000	-1	-	-	None

Table 7: Likelihood components by source.

Label	Total
TOTAL	1208.52
Catch	0.00
Equil catch	0.00
Length comp	96.62
Age comp	1109.68
Recruitment	2.10
InitEQ Regime	0.00
Forecast Recruitment	0.00
Parm priors	0.12
Parm softbounds	0.00
Parm devs	0.00
Crash Pen	0.00

Table 8: Time series of population estimates from the base model.

Year	Total Biomass (mt)	Spawning Output	Total Biomass 3+ (mt)	Fraction Unfished	Age-0 Recruits	Total Mortality (mt)	1-SPR	Exploitation Rate
1949	36.66	2.75	36.04	1.00	2.77	0.00	0.00	0.00
1950	36.69	2.75	36.04	1.00	2.93	0.01	0.01	0.00
1951	36.74	2.75	36.06	1.00	3.05	0.01	0.01	0.00
1952	36.83	2.74	36.11	1.00	3.06	0.03	0.02	0.00
1953	36.93	2.74	36.20	1.00	2.95	0.02	0.01	0.00
1954	37.07	2.74	36.35	1.00	2.78	0.04	0.02	0.00
1955	37.21	2.74	36.53	1.00	2.60	0.04	0.02	0.00
1956	37.35	2.74	36.71	1.00	2.47	0.07	0.04	0.00
1957	37.45	2.74	36.85	1.00	2.37	0.08	0.04	0.00
1958	37.53	2.74	36.95	1.00	2.32	0.06	0.03	0.00
1959	37.60	2.75	37.03	1.00	2.31	0.09	0.05	0.00
1960	37.60	2.76	37.05	1.00	2.33	0.04	0.02	0.00
1961	37.63	2.77	37.07	1.01	2.36	0.14	0.07	0.00
1962	37.53	2.78	36.97	1.01	2.41	0.12	0.06	0.00
1963	37.43	2.78	36.86	1.01	2.46	0.10	0.05	0.00
1964	37.34	2.79	36.75	1.02	2.53	0.08	0.04	0.00
1965	37.25	2.79	36.65	1.02	2.61	0.17	0.09	0.00
1966	37.08	2.78	36.46	1.01	2.73	0.14	0.07	0.00
1967	36.96	2.78	36.31	1.01	2.91	0.14	0.07	0.00
1968	36.87	2.77	36.19	1.01	3.17	0.14	0.07	0.00
1969	36.83	2.75	36.09	1.00	3.42	0.14	0.07	0.00
1970	36.84	2.74	36.05	1.00	3.41	0.14	0.07	0.00
1971	36.91	2.72	36.10	0.99	3.11	0.15	0.08	0.00
1972	37.01	2.71	36.24	0.99	2.76	0.15	0.08	0.00
1973	37.15	2.70	36.45	0.98	2.52	0.15	0.08	0.00
1974	37.28	2.70	36.65	0.98	2.40	0.15	0.08	0.00
1975	37.40	2.69	36.81	0.98	2.34	0.15	0.08	0.00
1976	37.48	2.70	36.92	0.98	2.23	0.09	0.05	0.00
1977	37.59	2.71	37.04	0.99	2.04	0.22	0.11	0.01
1978	37.50	2.72	36.99	0.99	1.83	0.19	0.10	0.01
1979	37.37	2.73	36.91	0.99	1.70	0.14	0.07	0.00
1980	37.22	2.74	36.79	1.00	1.69	0.17	0.09	0.00
1981	36.96	2.75	36.55	1.00	1.79	0.20	0.10	0.01
1982	36.62	2.76	36.21	1.00	1.92	0.10	0.05	0.00
1983	36.33	2.77	35.88	1.01	1.93	0.33	0.16	0.01
1984	35.75	2.75	35.30	1.00	1.81	0.54	0.24	0.02
1985	34.95	2.70	34.51	0.98	1.72	0.43	0.20	0.01
1986	34.25	2.66	33.82	0.97	1.77	0.28	0.14	0.01
1987	33.68	2.63	33.26	0.96	1.91	0.44	0.21	0.01
1988	32.95	2.58	32.51	0.94	2.03	0.54	0.25	0.02
1989	32.15	2.51	31.68	0.91	2.07	1.09	0.43	0.03
1990	30.84	2.40	30.36	0.87	1.97	0.91	0.39	0.03

Table 8: Time series of population estimates from the base model. *(continued)*

Year	Total Biomass (mt)	Spawning Output	Total Biomass 3+ (mt)	Fraction Unfished	Age-0 Recruits	Total Mortality (mt)	1-SPR	Exploitation Rate
1991	29.78	2.30	29.29	0.84	2.20	1.45	0.53	0.05
1992	28.26	2.16	27.77	0.79	2.30	1.49	0.56	0.05
1993	26.80	2.01	26.27	0.73	1.88	1.45	0.57	0.06
1994	25.46	1.88	24.94	0.68	2.23	1.06	0.50	0.04
1995	24.62	1.79	24.11	0.65	2.78	0.87	0.46	0.04
1996	24.06	1.72	23.46	0.62	3.03	0.84	0.46	0.04
1997	23.59	1.65	22.94	0.60	1.90	0.71	0.42	0.03
1998	23.33	1.61	22.72	0.58	2.08	0.49	0.33	0.02
1999	23.37	1.58	22.84	0.58	3.65	0.79	0.46	0.03
2000	23.37	1.54	22.54	0.56	8.49	0.64	0.40	0.03
2001	23.63	1.52	22.44	0.55	2.19	0.56	0.37	0.03
2002	24.05	1.51	22.73	0.55	1.31	0.30	0.23	0.01
2003	24.76	1.53	24.33	0.56	1.40	0.22	0.18	0.01
2004	25.54	1.56	25.19	0.57	2.05	0.19	0.15	0.01
2005	26.30	1.60	25.88	0.58	2.49	0.38	0.26	0.01
2006	26.93	1.63	26.29	0.59	5.87	0.44	0.29	0.02
2007	27.52	1.67	26.64	0.61	3.48	0.95	0.47	0.04
2008	27.59	1.68	26.50	0.61	1.62	0.56	0.33	0.02
2009	28.01	1.73	27.37	0.63	1.67	0.36	0.23	0.01
2010	28.57	1.79	28.15	0.65	2.63	0.74	0.38	0.03
2011	28.73	1.82	28.21	0.66	2.97	1.01	0.47	0.04
2012	28.55	1.82	27.93	0.66	1.77	0.95	0.45	0.03
2013	28.36	1.81	27.78	0.66	1.63	1.05	0.48	0.04
2014	28.00	1.81	27.58	0.66	1.81	1.04	0.48	0.04
2015	27.58	1.80	27.16	0.66	1.94	1.32	0.55	0.05
2016	26.84	1.77	26.38	0.64	2.24	0.82	0.42	0.03
2017	26.55	1.77	26.05	0.65	2.35	0.97	0.47	0.04
2018	26.08	1.76	25.54	0.64	2.35	1.24	0.54	0.05
2019	25.35	1.72	24.79	0.62	2.35	2.60	0.75	0.10
2020	23.31	1.56	22.75	0.57	2.32	0.66	0.40	0.03
2021	23.22	1.55	22.66	0.56	2.33	0.86	0.47	0.04
2022	22.95	1.52	22.39	0.55	2.32	0.84	0.47	0.04

Table 9: Likelihood, parameter and derivied quantities from data treatment sensitivities. The value of HIGH indicates unreasonable values.

	Reference	Length Only	CL	CL+Fr	CLA	CLA recs	Dirichlet	McI	no data-wt	1967 catch	Min Hist Ct	Max Hist Ct	Sex=3	CARE AE
AIC	2597.14	399.15	410.07	197.48	2772.50	2792.24	2816.98	1935.12	2597.14	2779.56	2779.32	2779.68	2605.90	2637.28
deltaAIC	0.00	-2197.99	-2187.07	-2399.66	175.36	195.10	219.84	-662.02	0.00	182.42	182.18	182.54	8.76	40.14
Length likelihood	96.64	195.57	202.04	95.74	99.71	82.16	184.16	128.28	96.64	183.02	182.96	183.05	101.83	95.44
Age likelihood	1109.68				1283.54	1231.47	1116.77	748.06	1109.68	1114.39	1114.42	1114.37	1109.89	1131.62
Parameters														
Female M	0.08	0.10	0.10	0.10	0.10	0.10	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.11
Female size at age 0	1.97	0.00	0.00	0.00	0.00	0.00	1.89	1.75	1.97	1.80	1.79	1.81	2.06	0.31
Female $L\infty$	57.10	53.87	53.87	53.87	53.87	53.87	57.30	57.27	57.10	57.29	57.29	57.29	57.16	56.47
Female k	0.09	0.12	0.12	0.12	0.12	0.12	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.10
Female CV_0	0.09	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.04
Female $CV@L\infty$	0.05	0.10	0.10	0.10	0.10	0.10	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06
Male M	0.09	0.10	0.10	0.10	0.10	0.10	0.08	0.08	0.09	0.08	0.09	0.08	0.09	0.12
Male size at age 0	-2.66	-3.19	-3.19	-3.19	-3.19	-3.19	-1.00	-1.09	-2.66	-1.03	-1.04	-1.02	-2.51	-3.68
Male $L\infty$	54.24	51.20	51.20	51.20	51.20	51.20	54.27	54.27	54.24	54.27	54.27	54.27	54.25	53.98
Male k	0.11	0.13	0.13	0.13	0.13	0.13	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Male CV_0	0.15	0.10	0.10	0.10	0.10	0.10	0.12	0.12	0.15	0.12	0.12	0.12	0.15	0.11
Male $CV@L\infty$	0.04	0.10	0.10	0.10	0.10	0.10	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
ln(R0)	0.90	8.23	1.14	1.14	2.47	18.71	0.74	0.75	0.90	0.75	0.78	0.74	0.89	3.63
Selectivity: Peak	44.25	49.07	45.62	45.62	43.53	43.33	45.15	44.98	44.25	45.10	45.12	45.09	44.15	44.29
Selectivity: Asc lt	4.14	4.60	4.28	4.28	4.05	4.18	4.27	4.24	4.14	4.26	4.26	4.26	4.10	4.14
Dirichlet Lts							3.91							
Dirichlet Ages							8.06							
Derived quantities														
$S0_0$	2.76		2.57	2.57	9.66	HIGH	2.76	2.72	2.76	2.75	2.72	2.77	2.79	24.27
$S0_{2021}$	1.55		1.46	1.46	8.54	HIGH	1.40	1.31	1.55	1.41	1.43	1.41	1.53	25.12
$Bratio_{2021}$	0.56	0.36	0.57	0.57	0.88	1.13	0.51	0.48	0.56	0.51	0.52	0.51	0.55	1.04
MSY_{SPR}	0.77		0.97	0.97	3.59	HIGH	0.69	0.68	0.77	0.69	0.70	0.69	0.76	8.43
F_{SPR}	0.05	0.09	0.07	0.07	0.07	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.07

Table 10: Likelihood, parameter and derivied quantities from life history model specification sensitivities. The value of HIGH indicates unreasonable values.

	Reference.Model	Fix LH	Fix M	Fix M, k, t0, CV	Fix.M, t0, CV	Fix M, CV	Fix M, Female Gr	Fix M, Male Gr	Fix growth	Fix Linf, CV	Fix.k, CV	Fix, CV	5 GTG
AIC	2597.14	2834.10	2584.54	2791.52	2737.46	2777.12	2709.78	2723.88	2834.16	2753.38	2795.04	2790.68	2780.46
deltaAIC	0.00	236.96	-12.60	194.38	140.32	179.98	112.64	126.74	237.02	156.24	197.90	193.54	183.32
Length likelihood	96.64	101.84	93.28	98.29	101.35	120.17	104.25	96.61	101.36	97.05	98.12	124.95	183.06
Age likelihood	1109.68	1232.27	1109.28	1211.29	1180.62	1179.63	1164.09	1178.61	1230.49	1192.57	1211.70	1180.33	1114.81
Parameters													
Female M	0.08	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.08	0.09	0.09	0.08	0.08
Female size at age 0	1.97	0.00	1.79	0.00	0.00	5.99	0.00	2.05	0.00	0.00	0.00	5.80	1.56
Female $L\infty$	57.10	53.87	57.05	51.20	56.43	57.95	53.87	57.03	53.87	53.87	51.33	57.83	57.36
Female k	0.09	0.12	0.09	0.12	0.09	0.08	0.12	0.09	0.12	0.10	0.12	0.08	0.09
Female CV_0	0.09	0.10	0.09	0.10	0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.10	0.10
Female $CV@L\infty$	0.05	0.10	0.05	0.10	0.10	0.10	0.10	0.05	0.10	0.10	0.10	0.10	0.06
Male M	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.08	0.10	0.09	0.09	0.08
Male size at age 0	-2.66	-3.19	-2.67	-3.19	-3.19	-0.48	-2.18	-3.19	-3.19	-3.19	-3.19	-0.97	-1.66
Male $L\infty$	54.24	51.20	54.25	48.94	54.32	54.19	54.23	51.20	51.20	51.20	49.00	54.09	54.27
Male k	0.11	0.13	0.11	0.13	0.10	0.10	0.11	0.13	0.13	0.12	0.13	0.10	0.11
Male CV_0	0.15	0.10	0.15	0.10	0.10	0.10	0.15	0.10	0.10	0.10	0.10	0.10	0.13
Male $CV@L\infty$	0.04	0.10	0.04	0.10	0.10	0.10	0.04	0.10	0.10	0.10	0.10	0.10	0.05
ln(R0)	0.90	18.75	1.77	1.47	1.72	1.57	6.80	2.97	0.89	1.11	1.02	0.84	0.67
Selectivity: Peak	44.25	43.43	44.25	57.95	45.96	47.17	42.96	44.02	43.36	49.20	57.13	46.95	45.51
Selectivity: Asc lt	4.14	4.19	4.13	5.38	4.25	4.36	4.07	4.20	4.20	4.63	5.36	4.36	4.32
Derived quantities													
$S0_0$	2.76	HIGH	4.59	2.69	4.01	3.51	715.52	15.08	3.46	2.61	2.33	2.67	2.66
$S0_{2021}$	1.55	HIGH	3.81	2.24	3.26	2.72	800.77	16.05	2.45	1.66	1.54	1.37	1.23
$Bratio_{2021}$	0.56	1.12	0.83	0.83	0.81	0.78	1.12	1.06	0.71	0.63	0.66	0.51	0.46
MSY_{SPR}	0.77	HIGH	1.56	1.22	1.48	1.27	257.20	5.35	0.91	0.88	0.85	0.72	0.64
F_{SPR}	0.05	0.06	0.06	0.15	0.07	0.07	0.06	0.06	0.05	0.07	0.12	0.06	0.05

Table 11: Likelihood, parameter and derivied quantities from model specification sensitivities that consider recruitment, fecundity, and domed selecitivity.

	Reference Model	No rec devs	σ_R = 0.45	σ_R = 0.75	Fec=wt	Dome-shaped sel	Lorenzen M
AIC	2597.14	2722.42	2597.14	2597.14	2597.20	2785.40	2596.96
deltaAIC	0.00	125.28	0.00	0.00	0.06	188.26	-0.18
Length likelihood	96.64	203.60	96.64	96.64	96.65	183.39	96.75
Age likelihood	1109.68	1142.59	1109.68	1109.68	1109.69	1114.07	1109.66
Parameters							
Female							
Female M	0.08	0.09	0.08	0.08	0.08	0.08	0.11
Female size age 0	1.97	2.20	1.97	1.97	1.97	1.40	1.39
Female $L\infty$	57.10	57.20	57.10	57.10	57.10	57.33	57.07
Female k	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Female CV_0	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Female $CV@L\infty$	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Male M	0.09	0.10	0.09	0.09	0.09	0.08	0.11
Male size age 0	-2.66	-1.37	-2.66	-2.66	-2.67	-0.99	-2.99
Male $L\infty$	54.24	54.36	54.24	54.24	54.24	54.41	54.30
Male k	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Male CV_0	0.15	0.14	0.15	0.15	0.15	0.12	0.15
Male $CV@L\infty$	0.04	0.04	0.04	0.04	0.04	0.04	0.04
ln(R0)	0.90	1.08	0.90	0.90	0.91	0.83	1.81
σ_R	0.60	0.70	0.60	0.60	0.60	0.60	0.60
Sel: Peak	44.25	44.65	44.25	44.25	44.25	45.00	44.72
Sel: Top width	15.00	15.00	15.00	15.00	15.00	-1.54	15
Sel: Asc lt	4.14	4.11	4.14	4.14	4.14	4.25	4.13
Sel: Desc lt	-15.00	-15.00	-15.00	-15.00	-15.00	-2.01	-15
Sel: End selectivity	15.00	15.00	15.00	15.00	15.00	2.18	15
Derived quantities							
$S0_0$	2.76	2.76	2.76	2.76	15.11	2.96	2.81
$S0_{2021}$	1.55	1.38	1.55	1.55	8.64	1.64	1.61
$Bratio_{2021}$	0.56	0.50	0.56	0.56	0.57	0.55	0.57
MSY_{SPR}	0.77	0.80	0.77	0.77	0.79	0.74	0.79
F_{SPR}	0.05	0.06	0.05	0.05	0.05	0.05	0.05

Table 12: Summary of reference points and management quantities, including estimates of the 95 percent intervals.

	Estimate	Lower Interval	Upper Interval
Unfished Spawning Output	2.75	0.74	4.75
Unfished Age 3+ Biomass (mt)	36.04	8.49	63.60
Unfished Recruitment (R0)	2.48	0.00	5.46
Spawning Output (2021)	1.55	0.00	4.00
Fraction Unfished (2021)	0.56	0.06	1.07
Reference Points Based SB40%			
Proxy Spawning Output SB40%	1.10	0.30	1.90
SPR Resulting in SB40%	0.46	0.46	0.46
Exploitation Rate Resulting in SB40%	0.06	0.04	0.08
Yield with SPR Based On SB40% (mt)	0.81	0.05	1.57
Reference Points Based on SPR Proxy for MSY			
Proxy Spawning Output (SPR50)	1.23	0.33	2.12
SPR50	0.50		
Exploitation Rate Corresponding to SPR50	0.05	0.04	0.07
Yield with SPR50 at SB SPR (mt)	0.77	0.05	1.49
Reference Points Based on Estimated MSY Values			
Spawning Output at MSY (SB MSY)	0.75	0.28	1.22
SPR MSY	0.34	0.32	0.37
Exploitation Rate Corresponding to SPR MSY	0.09	0.06	0.13
MSY (mt)	0.87	0.05	1.70

Table 13: Projections of potential OFLs (mt), ABCs (mt), the buffer (ABC = buffer x OFL), estimated spawning biomass, and fraction unfished. The North of 40°10'N OFL and ABC for 2021 and 2022 are included for comparison.

Year	OFL 40°10'N	ACL 40°10'N	Predicted OFL	ABC Catch	Buffer	Spawning Output	Fraction Unfished
2021	9.7	8.1	0.94	2.69	1.00	1.55	0.56
2022	9.7	8.1	0.84	3.26	1.00	1.37	0.50
2023	-	-	0.70	0.61	0.87	1.15	0.42
2024	-	-	0.70	0.61	0.87	1.14	0.42
2025	-	-	0.70	0.61	0.86	1.13	0.41
2026	-	-	0.71	0.61	0.85	1.13	0.42
2027	-	-	0.72	0.61	0.84	1.13	0.42
2028	-	-	0.73	0.61	0.83	1.13	0.43
2029	-	-	0.74	0.62	0.83	1.14	0.43
2030	-	-	0.75	0.62	0.82	1.14	0.43
2031	-	-	0.76	0.62	0.81	1.15	0.44
2032	-	-	0.77	0.62	0.80	1.16	0.44

Table 14: Decision table summary of 10 year projections beginning in 2023 for alternative states of nature based on an axis of uncertainty about female and male natural mortality for the reference model. Columns range over low (12.5 quantile), mid (reference model), and high states (87.5 quantile) of nature and rows range over different catch level assumptions. Values in italics indicate years where the stock size prevented the full catch removals.

			Female M = 0.067; Male =0.069		Female M = 0.084; Male =0.086		Female M = 0.099; Male =0.100	
	Year	Catch	Spawning Output	Fraction Unfished	Spawning Output	Fraction Unfished	Spawning Output	Fraction Unfished
P*=0.45 sigma=1.0	2021	2.69	0.68	0.31	1.55	0.56	3.62	0.81
	2022	3.26	0.50	0.23	1.38	0.50	3.44	0.77
	2023	0.62	0.28	0.13	1.16	0.42	3.21	0.72
	2024	0.61	0.26	0.12	1.15	0.42	3.20	0.72
	2025	0.61	0.25	0.11	1.15	0.42	3.19	0.72
	2026	0.61	0.24	0.11	1.15	0.42	3.18	0.72
	2027	0.61	0.24	0.11	1.16	0.42	3.18	0.72
	2028	0.62	0.24	0.11	1.17	0.43	3.19	0.72
	2029	0.62	0.24	0.11	1.18	0.43	3.20	0.72
	2030	0.62	0.24	0.11	1.20	0.44	3.21	0.72
	2031	0.63	0.24	0.11	1.21	0.44	3.23	0.73
	2032	0.63	0.24	0.11	1.23	0.45	3.24	0.73
P*=0.4 sigma=1.0	2021	2.69	0.68	0.31	1.55	0.56	3.62	0.81
	2022	3.26	0.50	0.23	1.38	0.50	3.44	0.77
	2023	0.54	0.28	0.13	1.16	0.42	3.21	0.72
	2024	0.53	0.27	0.12	1.16	0.42	3.20	0.72
	2025	0.53	0.26	0.12	1.16	0.42	3.20	0.72
	2026	0.53	0.26	0.12	1.17	0.43	3.20	0.72
	2027	0.53	0.26	0.12	1.18	0.43	3.21	0.72
	2028	0.53	0.27	0.12	1.20	0.44	3.22	0.72
	2029	0.53	0.27	0.12	1.22	0.44	3.24	0.73
	2030	0.53	0.28	0.13	1.24	0.45	3.26	0.73
	2031	0.52	0.29	0.13	1.26	0.46	3.28	0.74
	2032	0.52	0.30	0.13	1.28	0.47	3.30	0.74
FMSY proxy SPR=0.5	2021	2.69	0.68	0.31	1.55	0.56	3.62	0.81
	2022	3.26	0.50	0.22	1.38	0.50	3.44	0.77
	2023	0.77	0.28	0.13	1.15	0.42	3.21	0.72
	2024	0.77	0.25	0.11	1.14	0.41	3.18	0.72
	2025	0.77	0.23	0.10	1.12	0.41	3.16	0.71
	2026	0.77	0.21	0.09	1.11	0.40	3.15	0.71
	2027	0.77	0.19	0.09	1.11	0.40	3.14	0.71
	2028	0.77	0.18	0.08	1.11	0.40	3.13	0.70
	2029	0.77	0.17	0.08	1.11	0.40	3.13	0.70
	2030	0.77	0.16	0.07	1.11	0.40	3.13	0.70
	2031	0.77	0.15	0.07	1.12	0.41	3.14	0.71
	2032	0.77	0.14	0.06	1.12	0.41	3.15	0.71

7 Figures

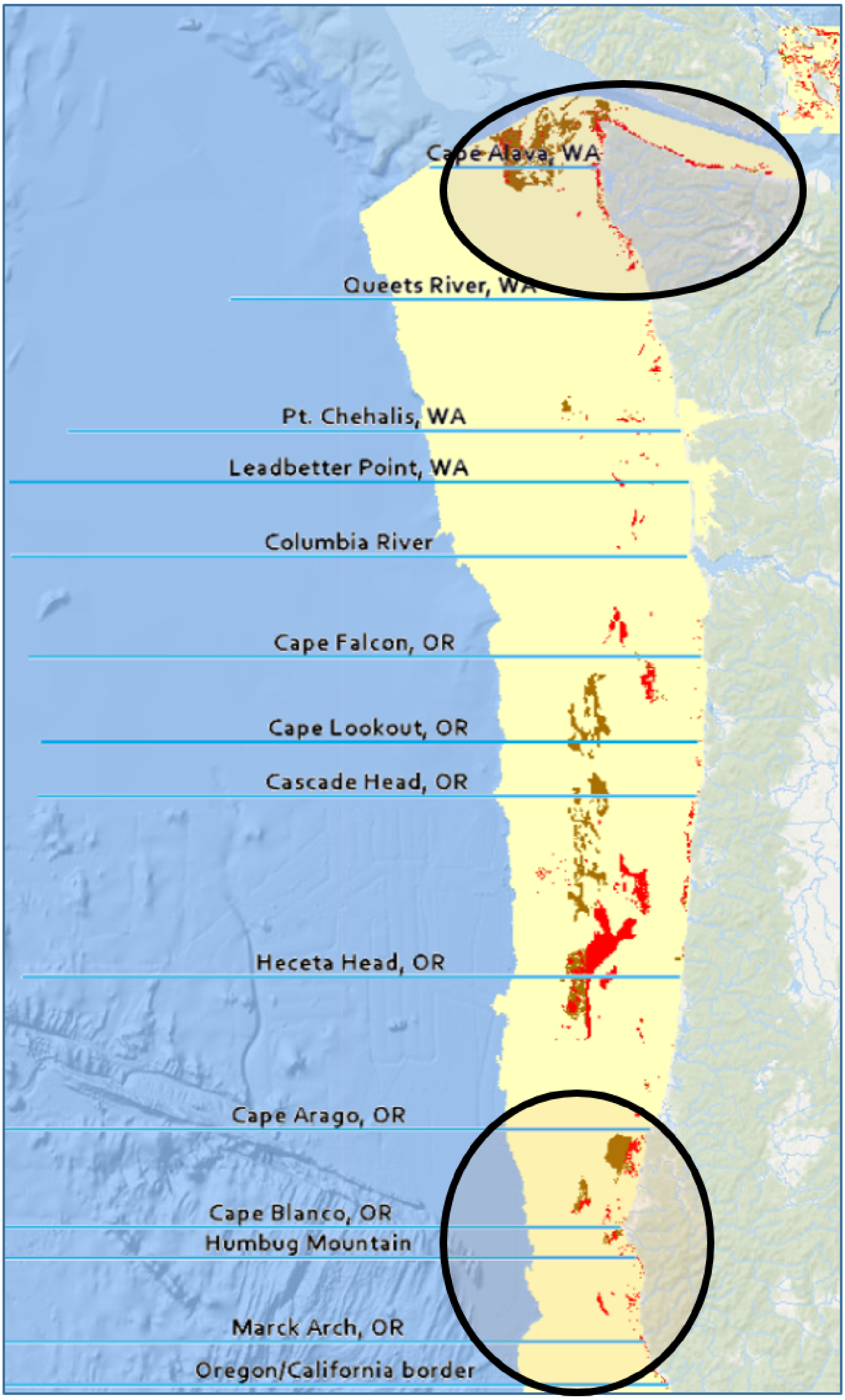

Figure 1: Oregon and Washington coastlines with rocky habitat indicated by brown shaded areas. Circled areas represent areas of primary vermilion rockfish occurence.

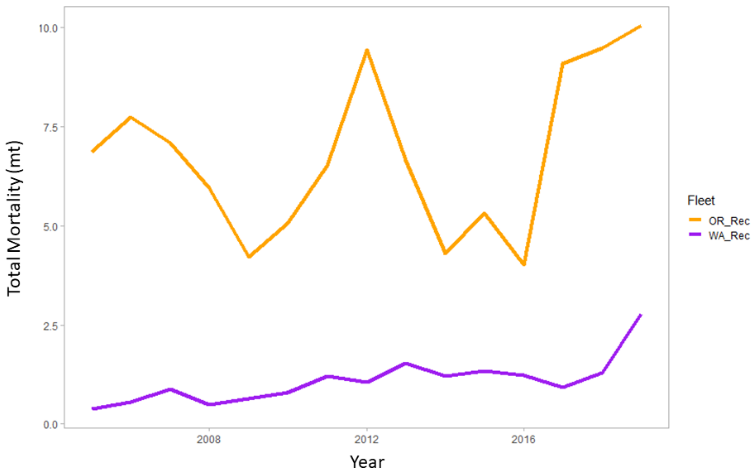

Figure 2: Total mortality from the southern Oregon and northern Washington recreational fisheries. These represent ninety and ninety-seven percent of the total vermilion rockfish removals in each state, respectively.

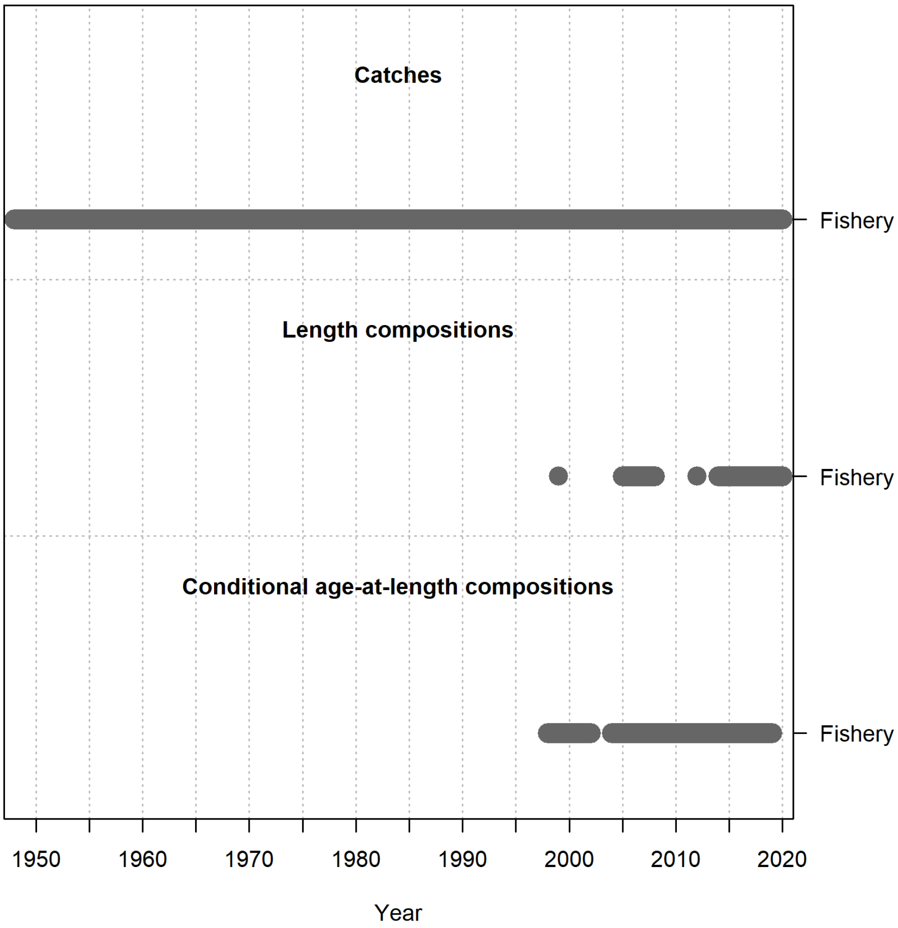

Figure 3: Summary of data sources used in the reference model.

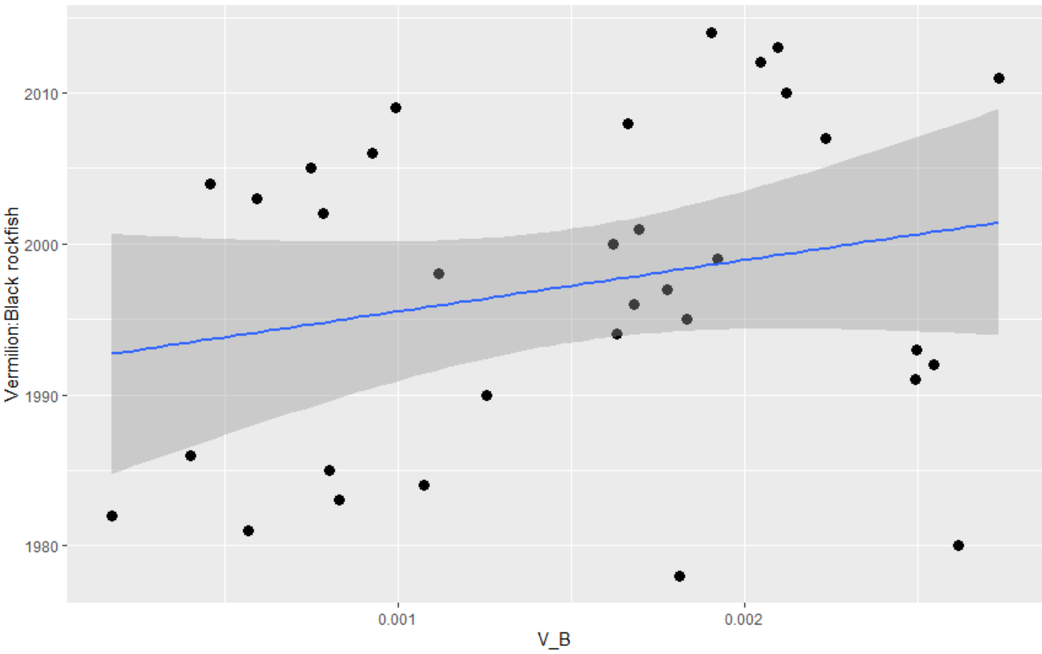

Figure 4: Plot of year to the vermilion:black rockfish (V_B) landing ratio. The linear model presented was used to predict vermilion rockfish catch from black rockfish catch for years of missing vermilion rockfish landings. The linear (y=ax+b) coefficients were a= 0.000016 and b= 0.029710.

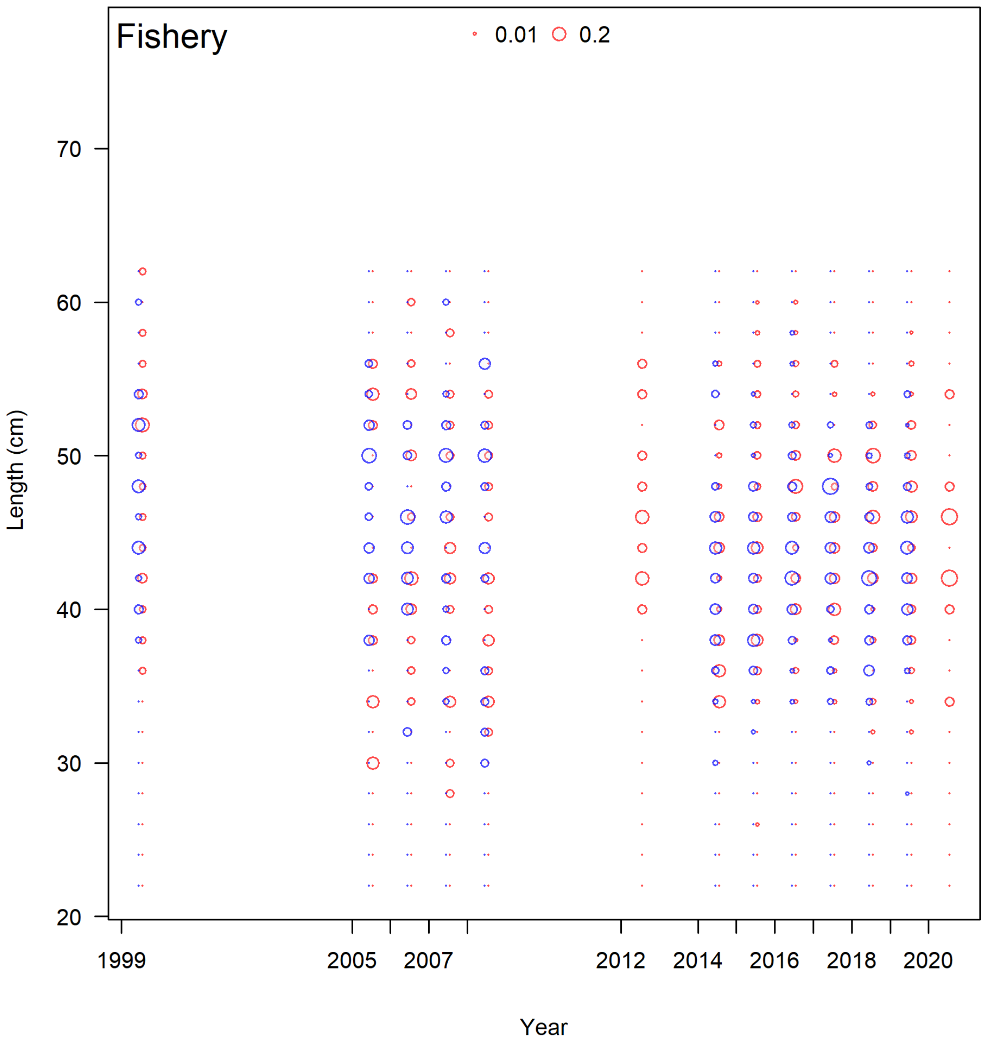

Figure 5: Bubble plot of length compositions by year. Size of the bubble indicates higher proportion. All proportions within year sum to one.

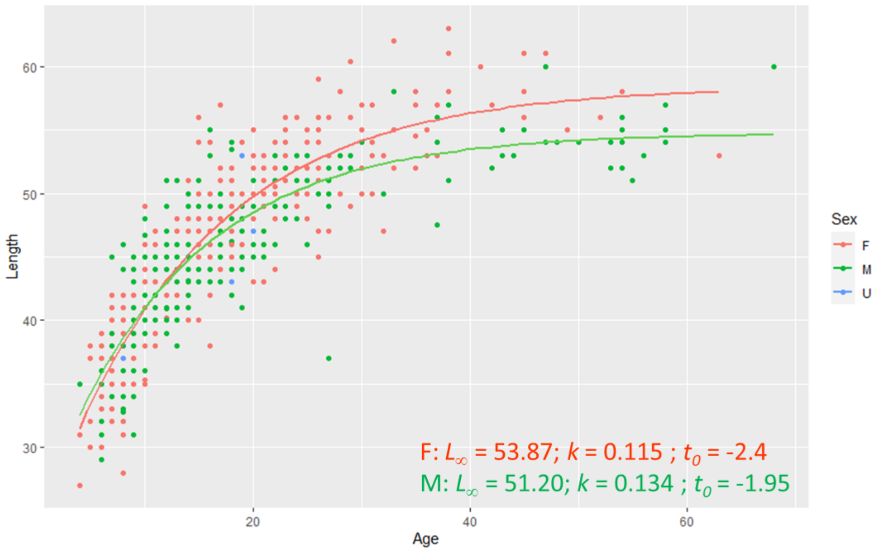

Figure 6: Observed length-at-age by data source and sex. Lines indicate fits to the von Bertalanffy growth equation, with initial parameter estimates provided in the bottom right corner of the figure.

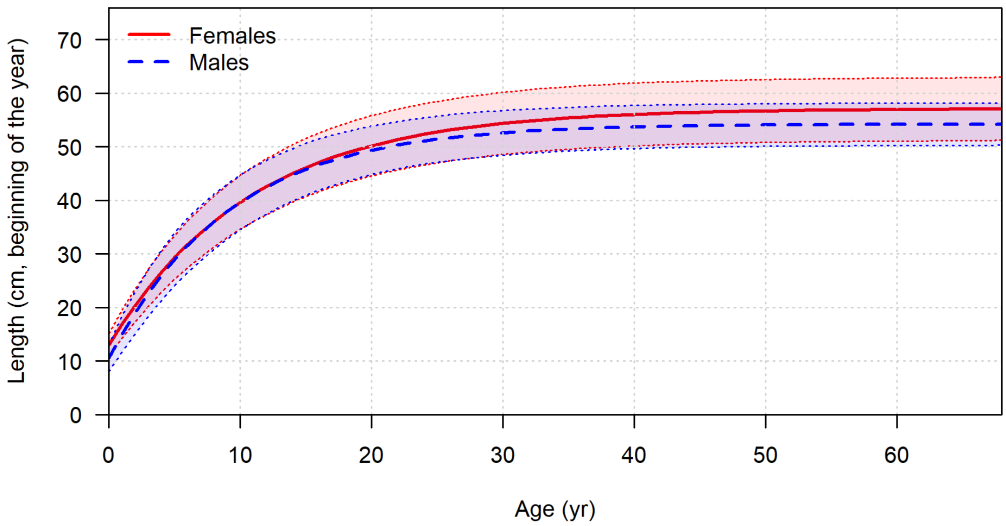

Figure 7: Model estimated length-at-age in the beginning of the year. Shaded area indicates 95 percent distribution of length-at-age around the estimated growth curve.

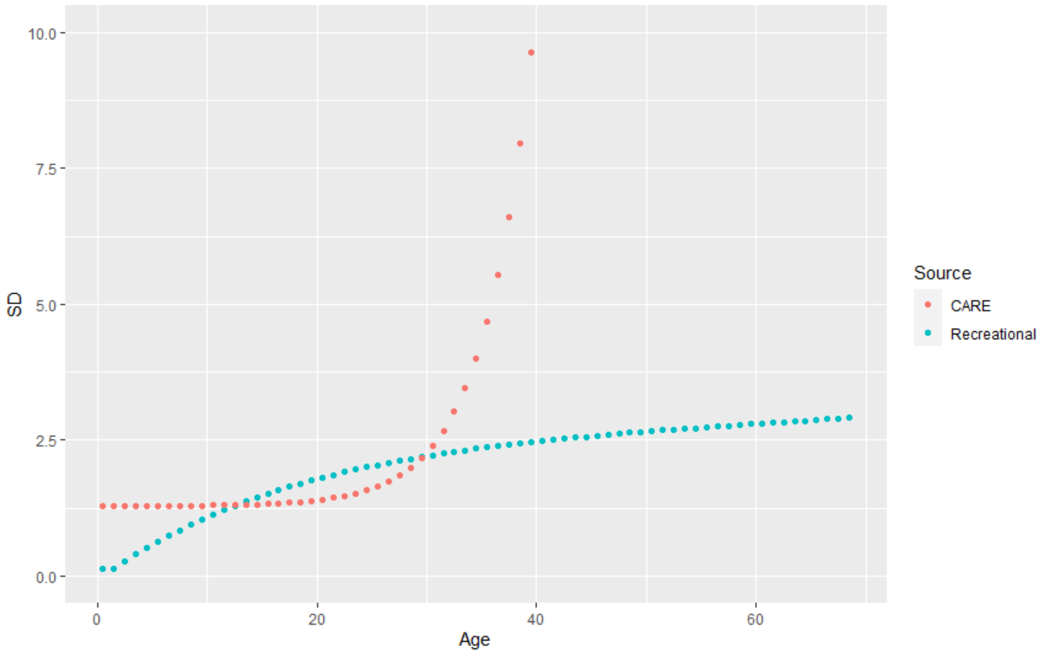

Figure 8: Ageing error matrix (age by standard deviation (SD)) values by source. The recreational matrix is based on intra-reader comparisons.

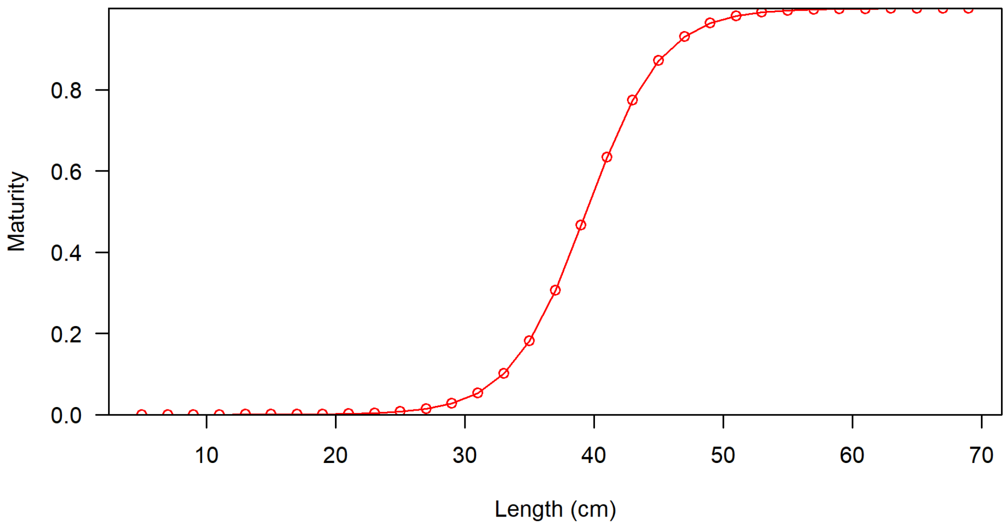

Figure 9: Maturity as a function of length (cm).

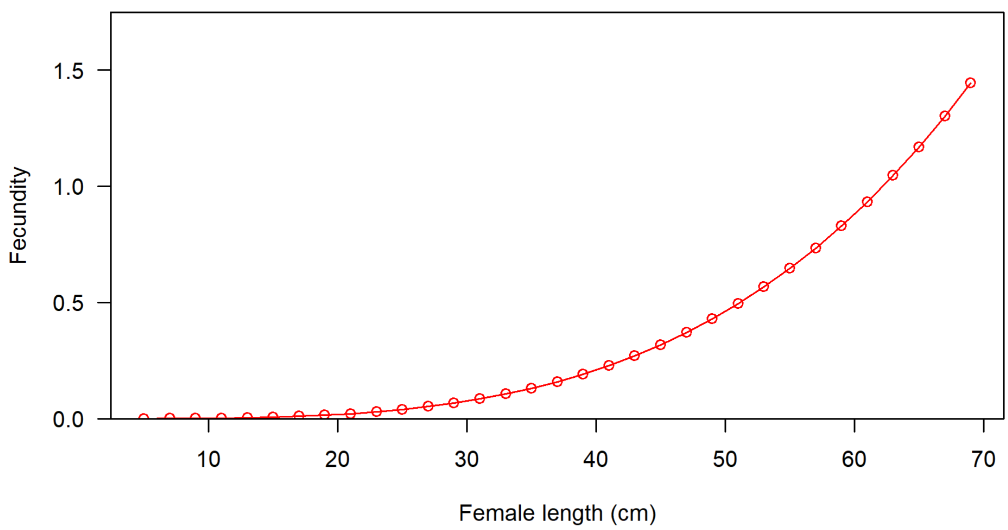

Figure 10: Fecundity (kg) as a function of length (cm).

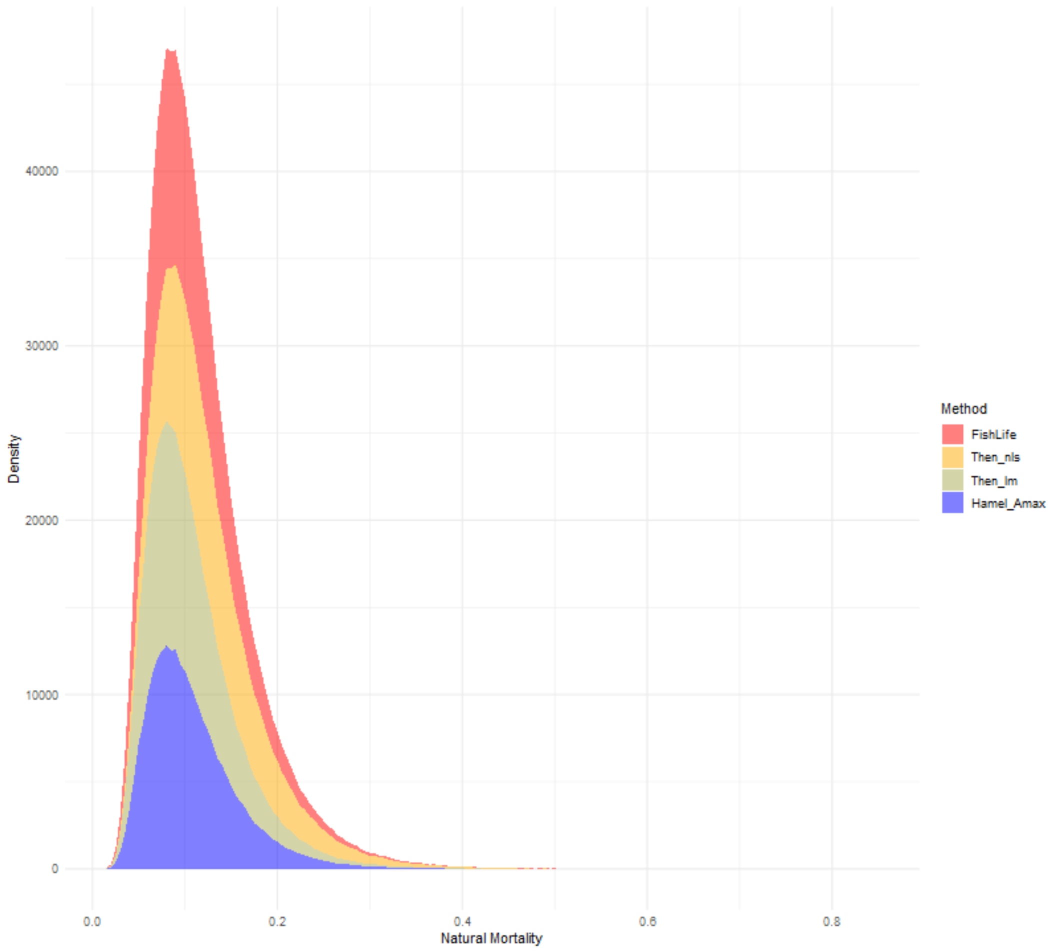

Figure 11: Composite natural mortality distriubtion for vermilion rockfish using four longevity estimators each with a SD = 0.438 presuming a lognomral error distibution.

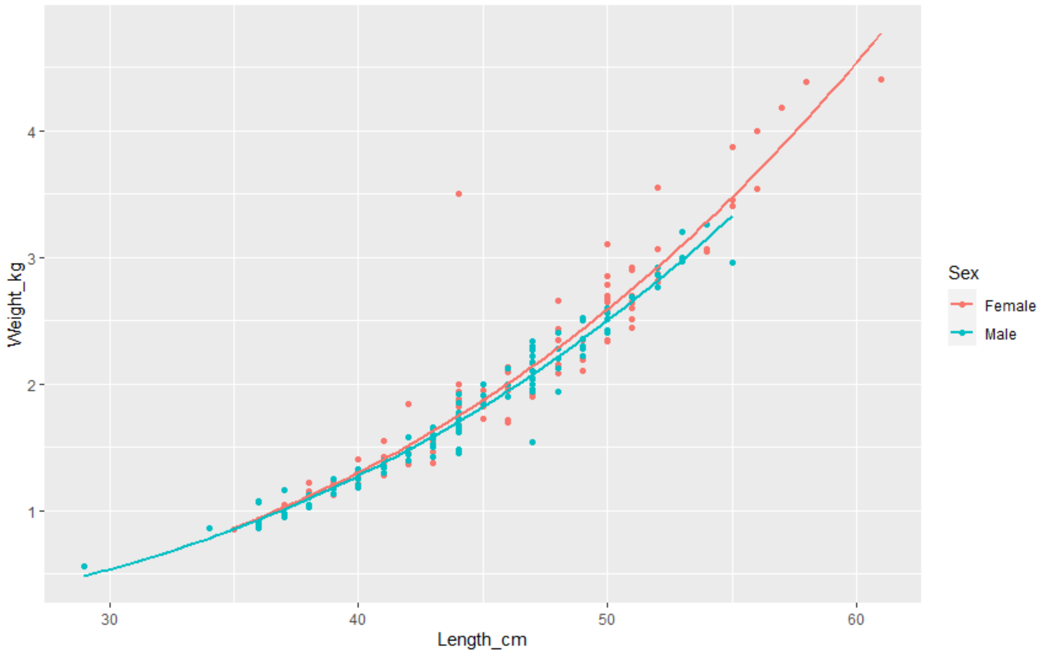

Figure 12: Length (cm)-weight (kg) data and fits to sex-specific vermilion rockfish samples from the recreational fishery.

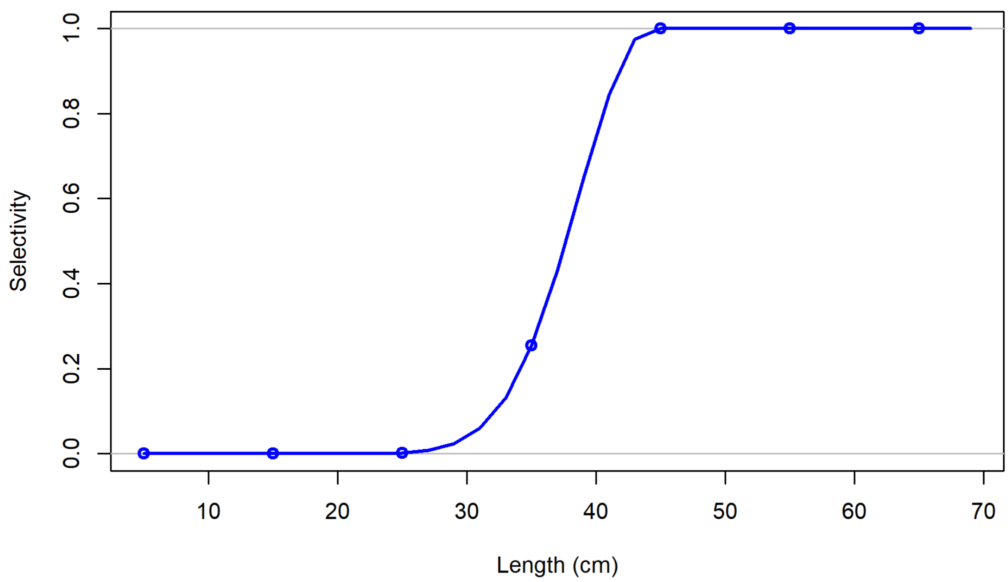

Figure 13: Selectivity at length (cm) by fleet.

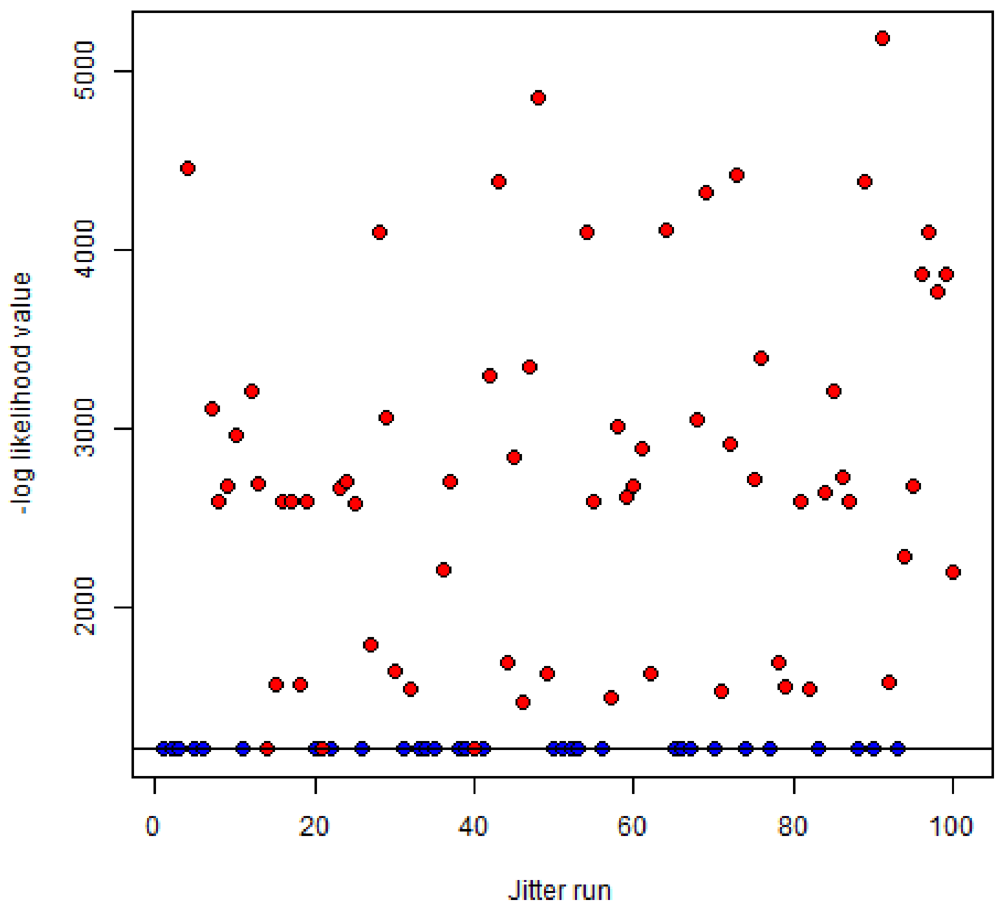

Figure 14: Jitter runs for the vermilion rockfish reference model, with jitter run number on the x-axis and -log likelihood value on the y-axis. Blue dot are models that match the likelihood value of the reference model, while red dots deviate from the reference model. All red dots are above the blue dots, indicating no better fit to the reference model was found.

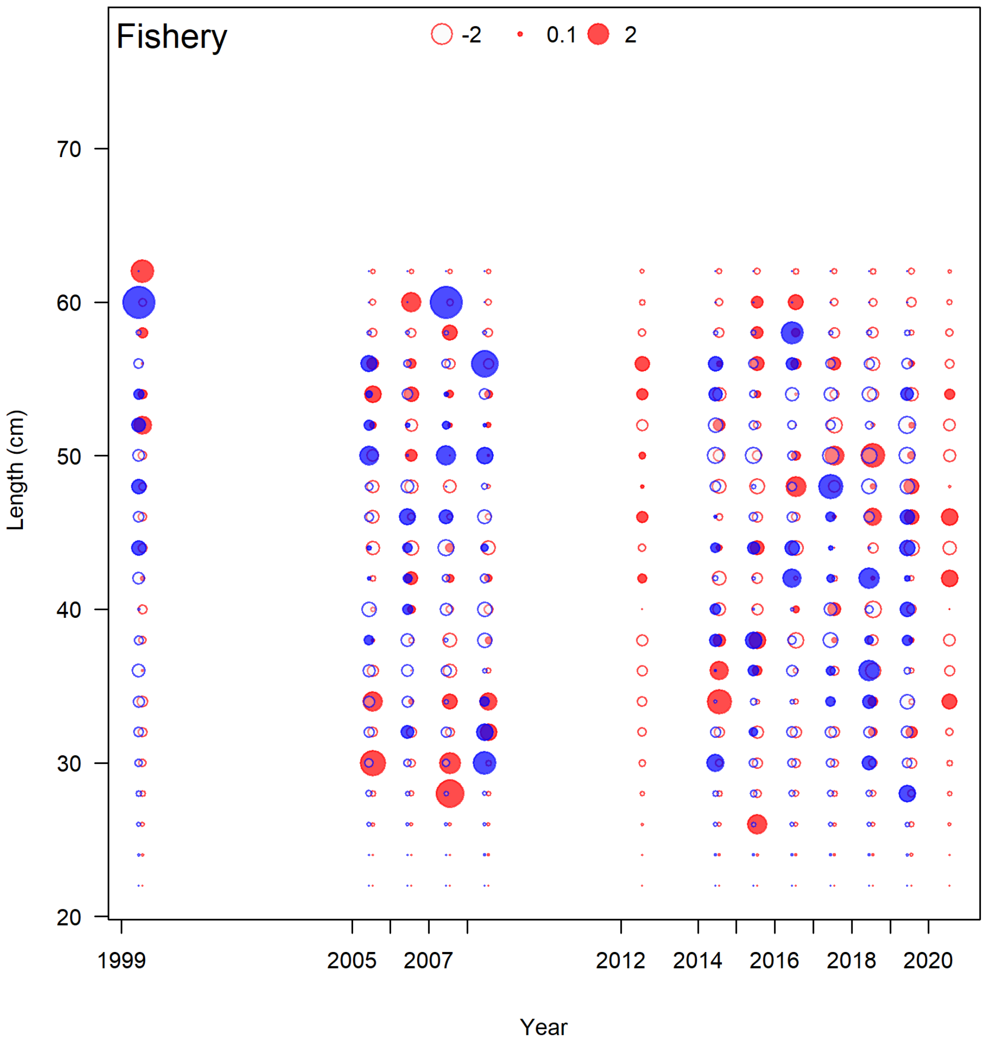

Figure 15: Pearson residuals for the recreational fleet. Closed bubble are positive residuals (observed > expected) and open bubbles are negative residuals (observed < expected).

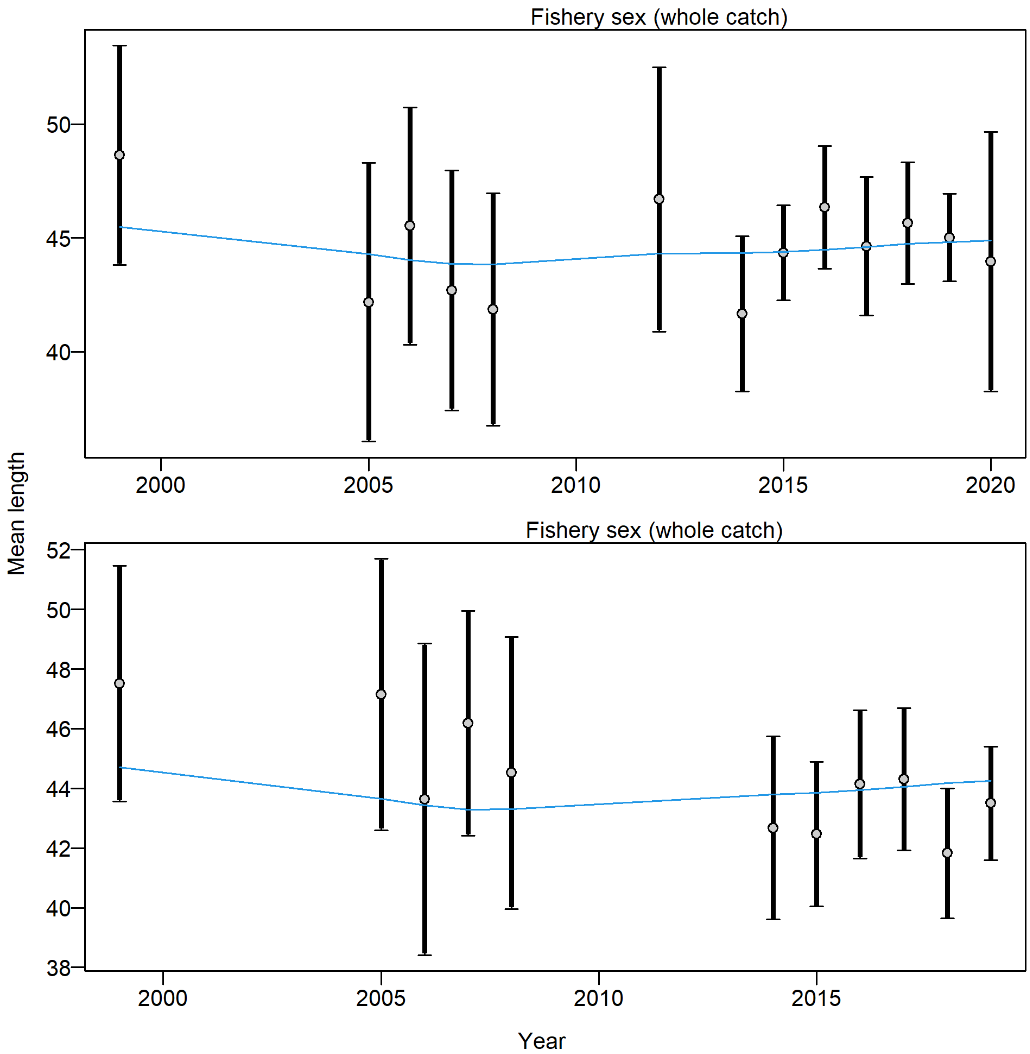

Figure 16: Mean length (cm) index from the recreational fishery with 95 percent confidence intervals based on sample sizes and data weighting.

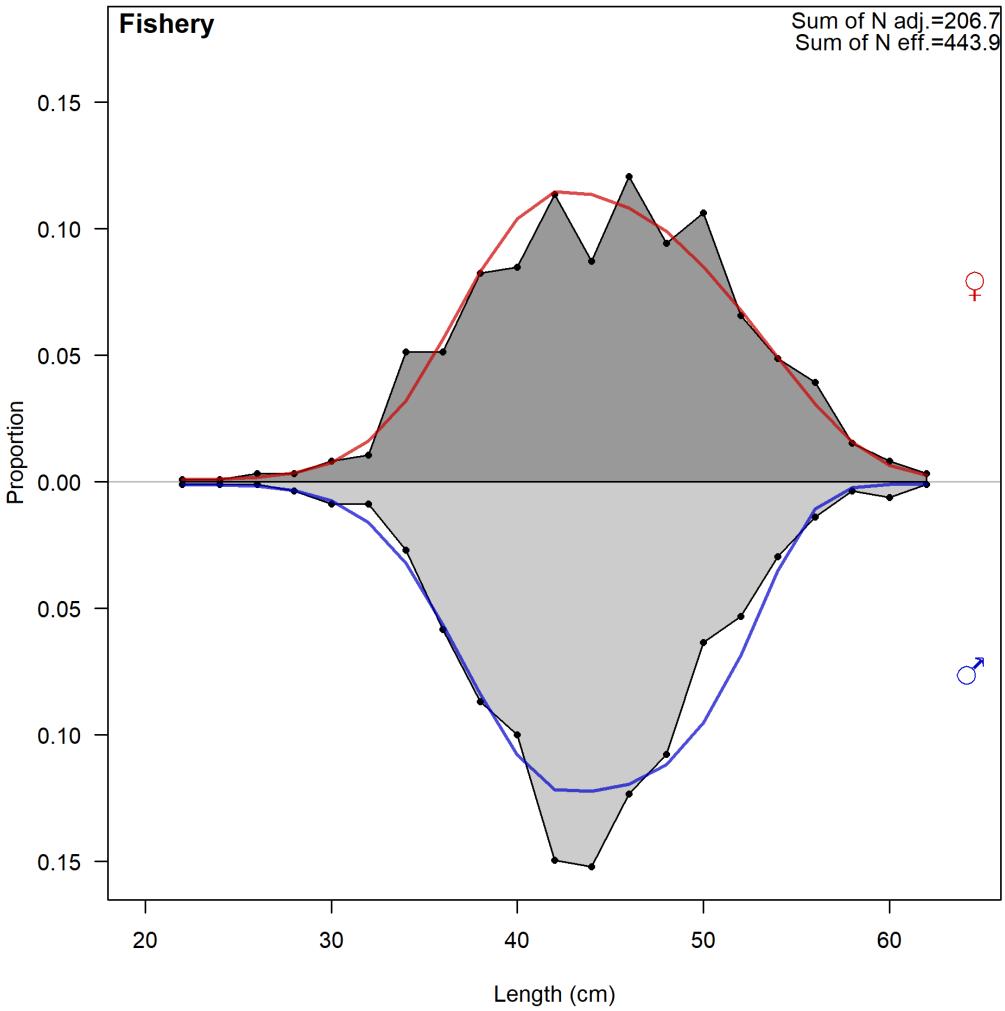

Figure 17: Aggregated length (cm) compositions over all years.

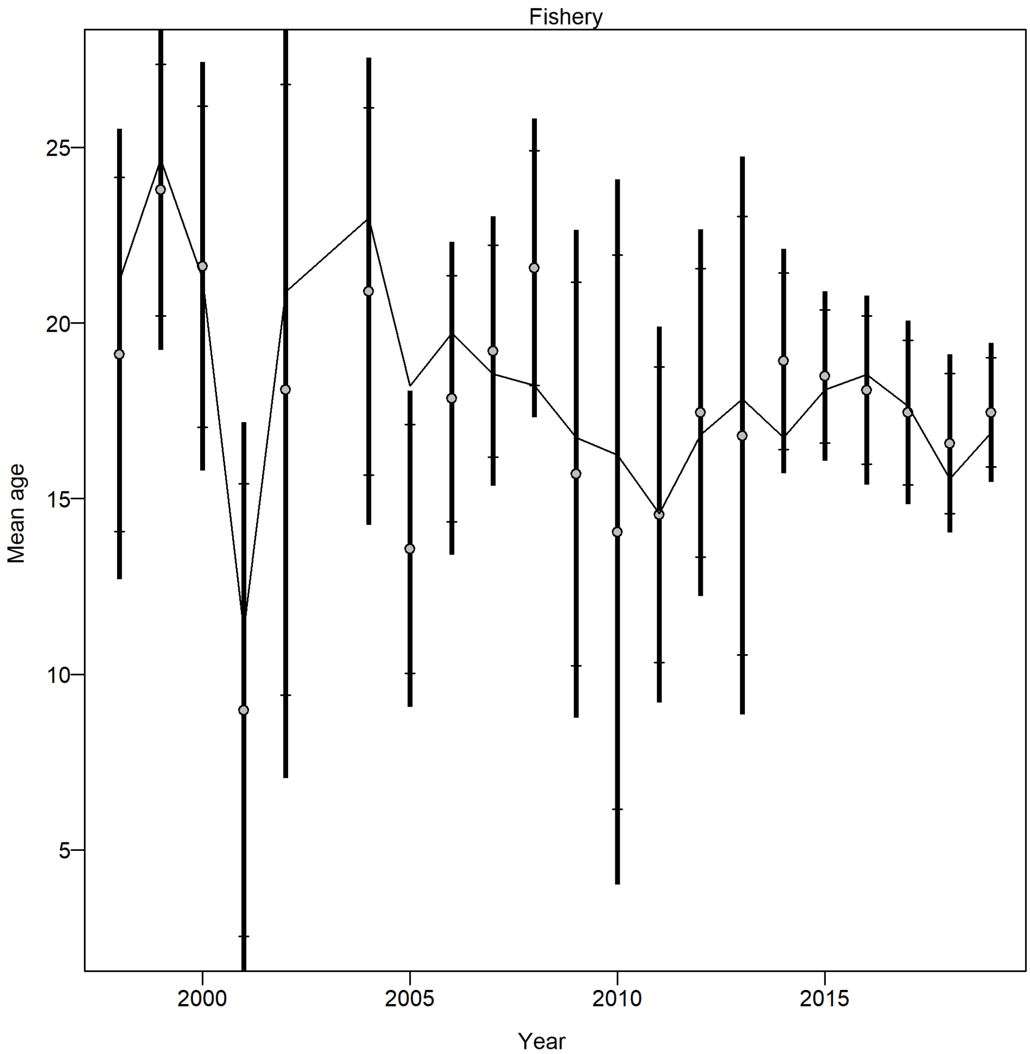

Figure 18: Mean age observations from the conditional age-at-length (cm) data from the recreational fishery.

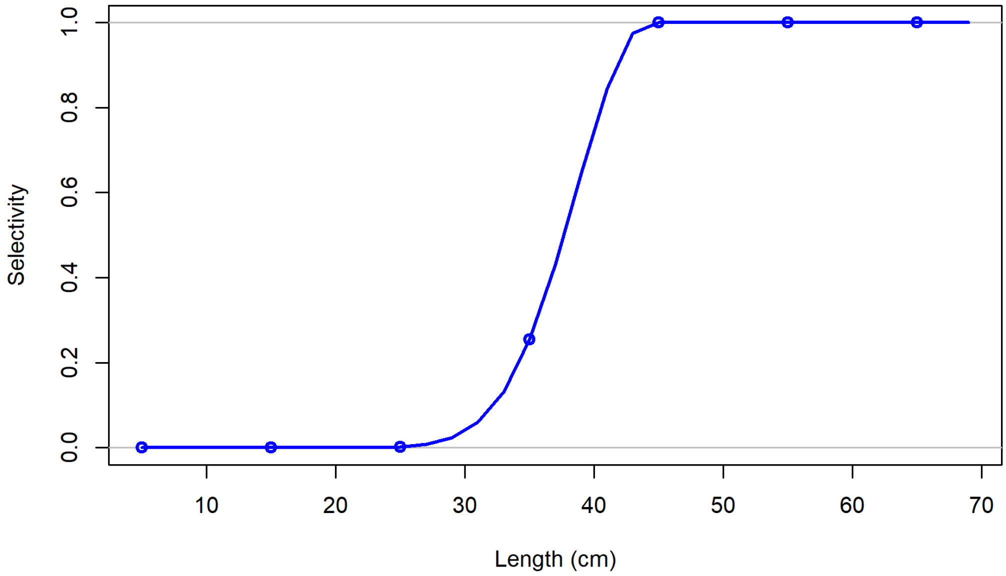

Figure 19: Length-based selectivity curves for the commercial and recreational fisheries.

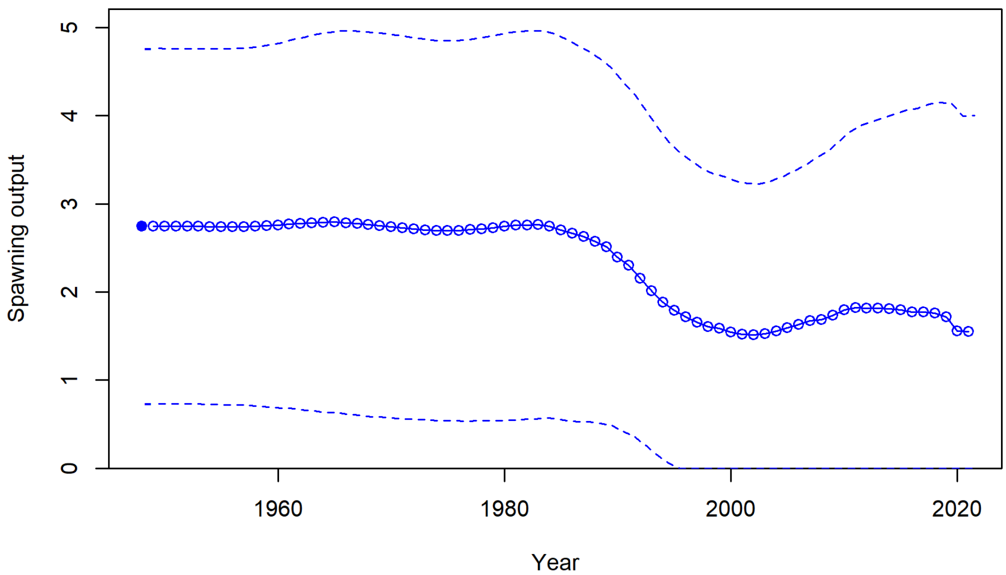

Figure 20: Estimated time series of spawning output (in millions of eggs). Values at or less than zero are not realistic and result from the normality assumption of the asymptotic variance estimation.

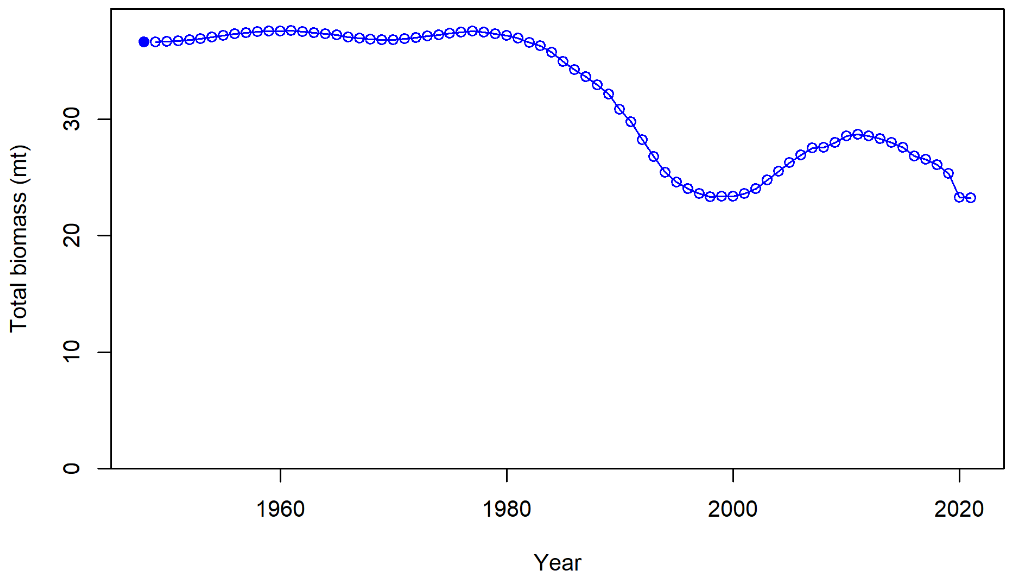

Figure 21: Estimated time series of total biomass (mt).

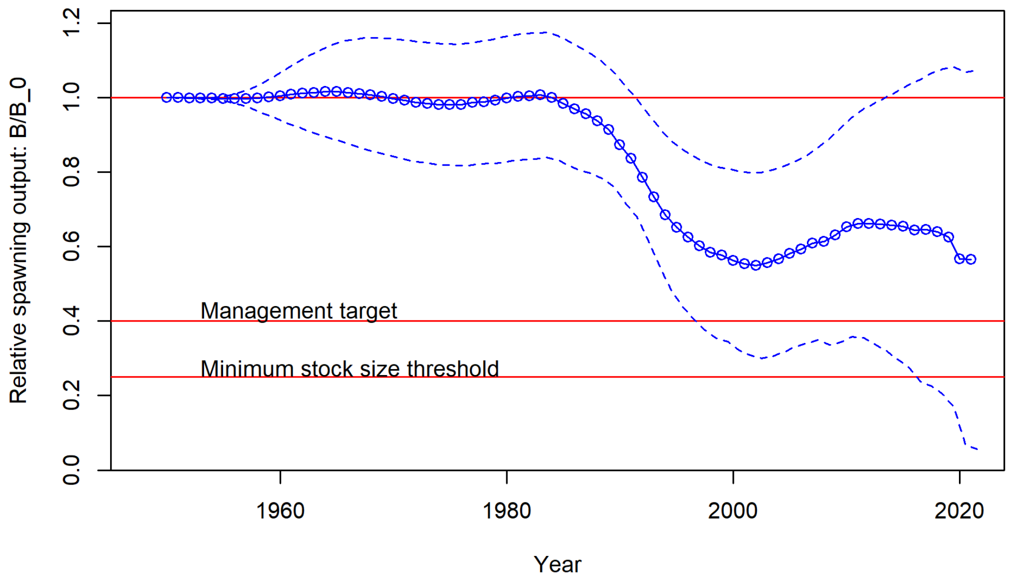

Figure 22: Estimated time series of fraction of unfished spawning output.

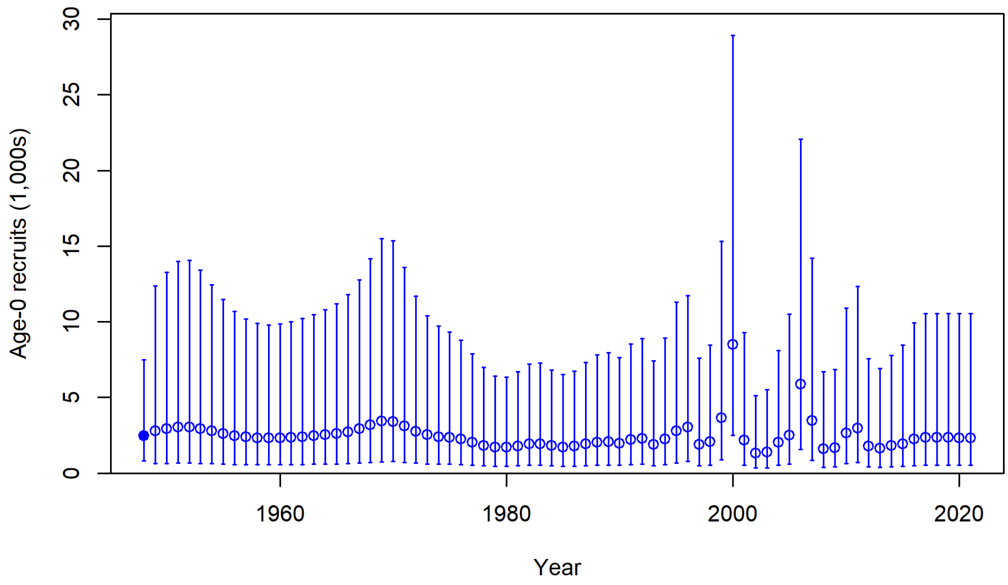

Figure 23: Estimated time series of age-0 recruits (1000s).

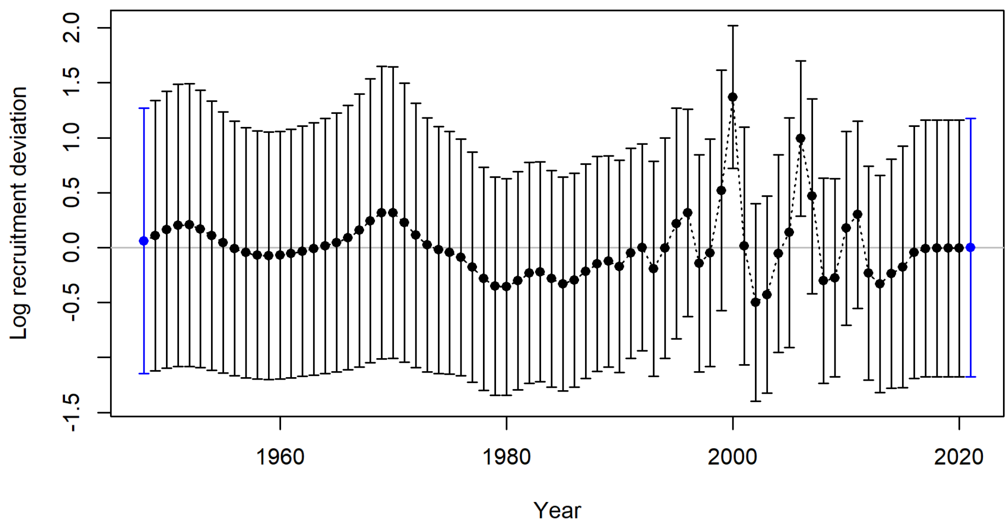

Figure 24: Estimated time series of recruitment deviations.

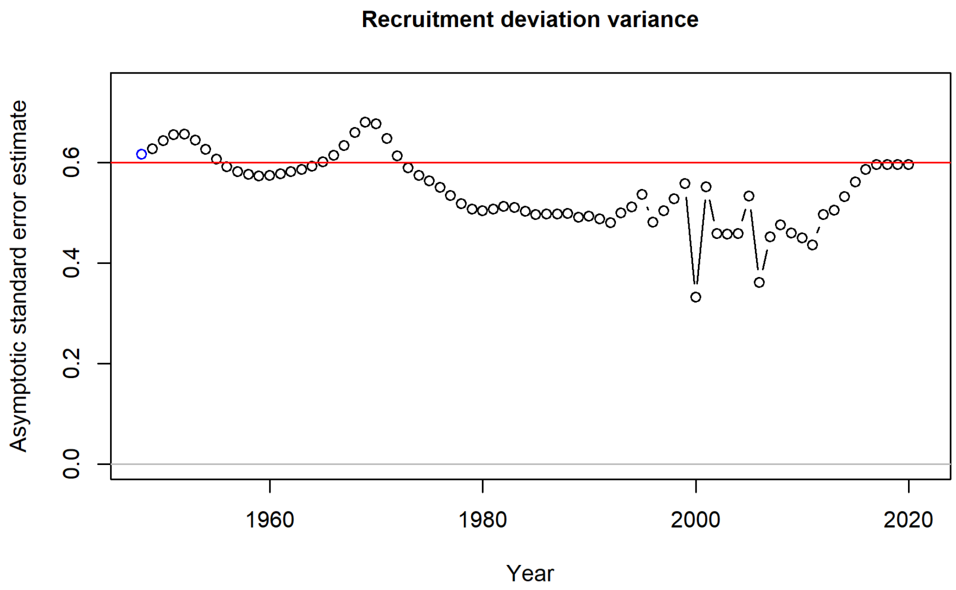

Figure 25: Recruitment deviations variance by year. This plot tracks the information content contained in each recruitment deviation. Values below the red line (assumed recruitment variability) indicates years with more informed recruitment deviations.

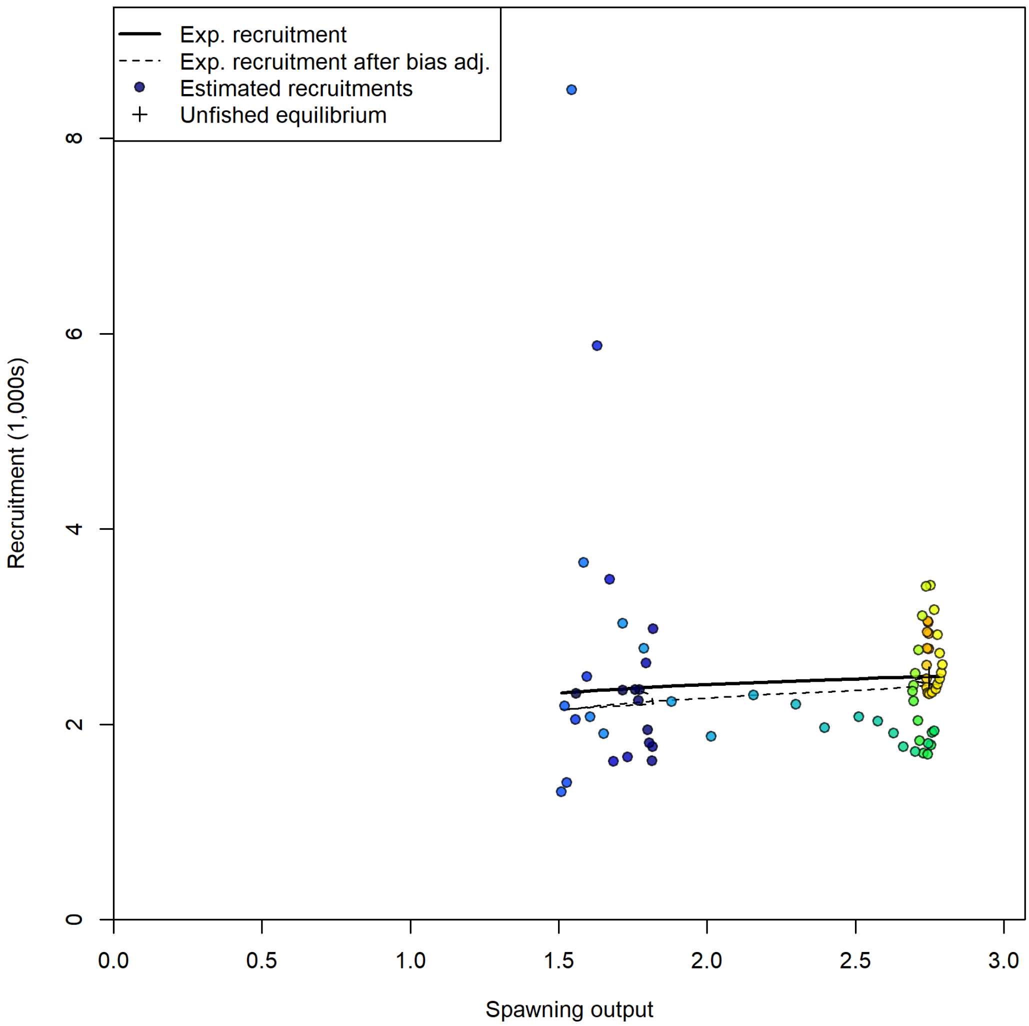

Figure 26: Stock-recruit curve. Point colors indicate year, with warmer colors indicating earlier years and cooler colors in showing later years.

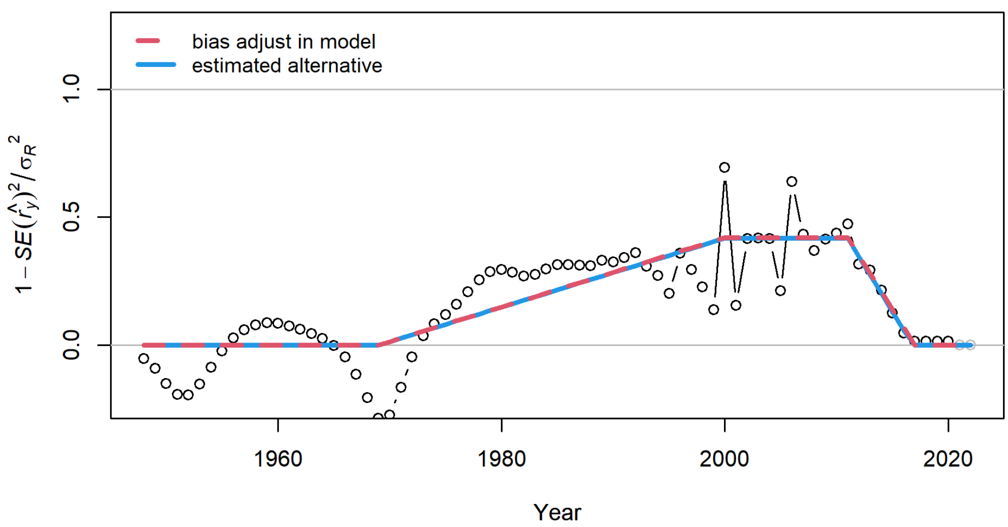

Figure 27: Recruitment bias adjustment applied in the reference model.

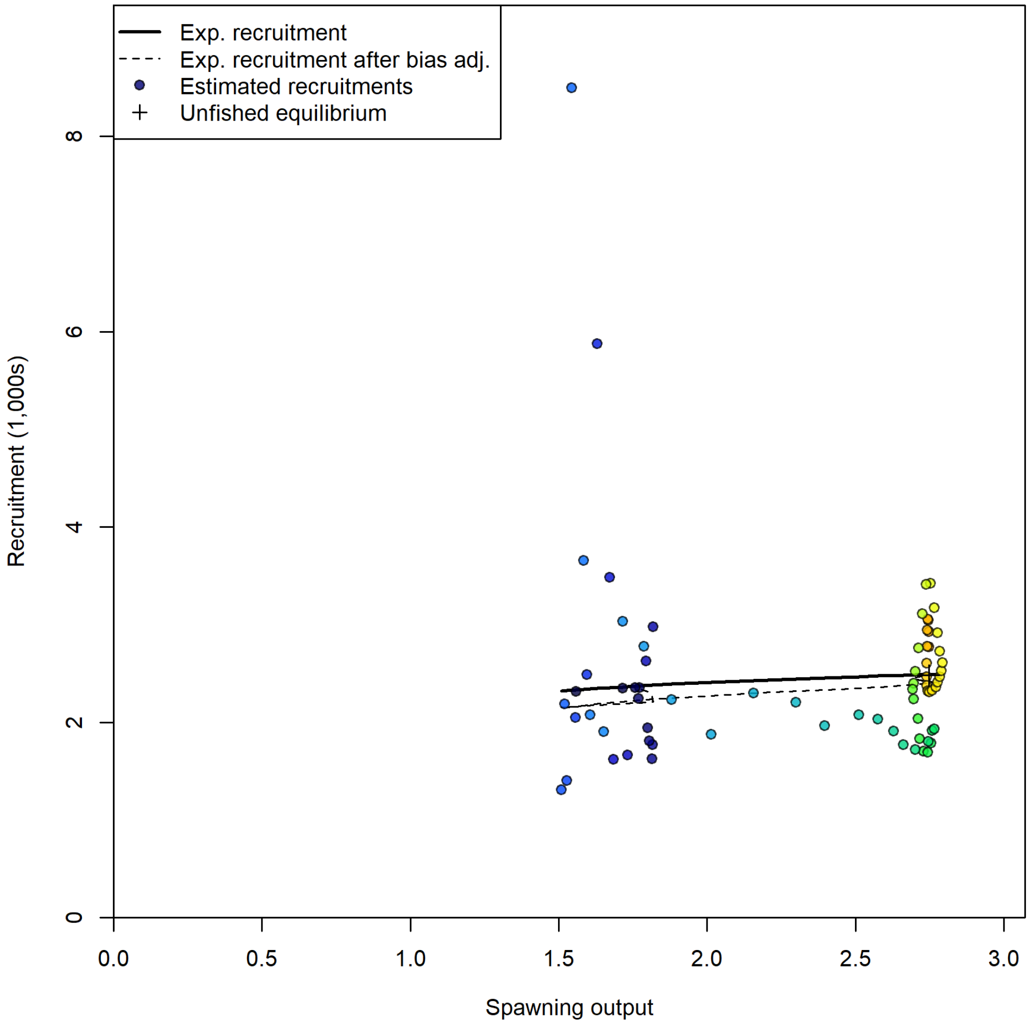

Figure 28: Stock recruit curve where point color indicates year, with warmer colors (yellow to green) indicating earlier years and cooler colors (blue) showing later years.

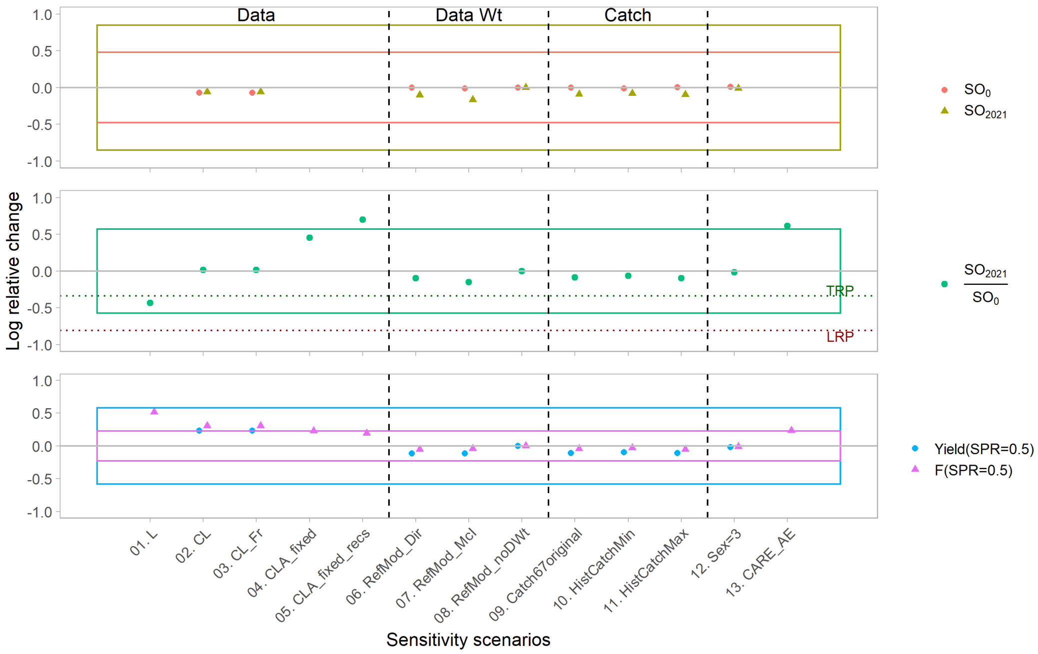

Figure 29: Log relative change (log((Model_sensi-Model_ref)/Model_ref)) in data treatment for 5 derived quantities. Colored boxes indicate 95 percent confidence interval of the reference model.

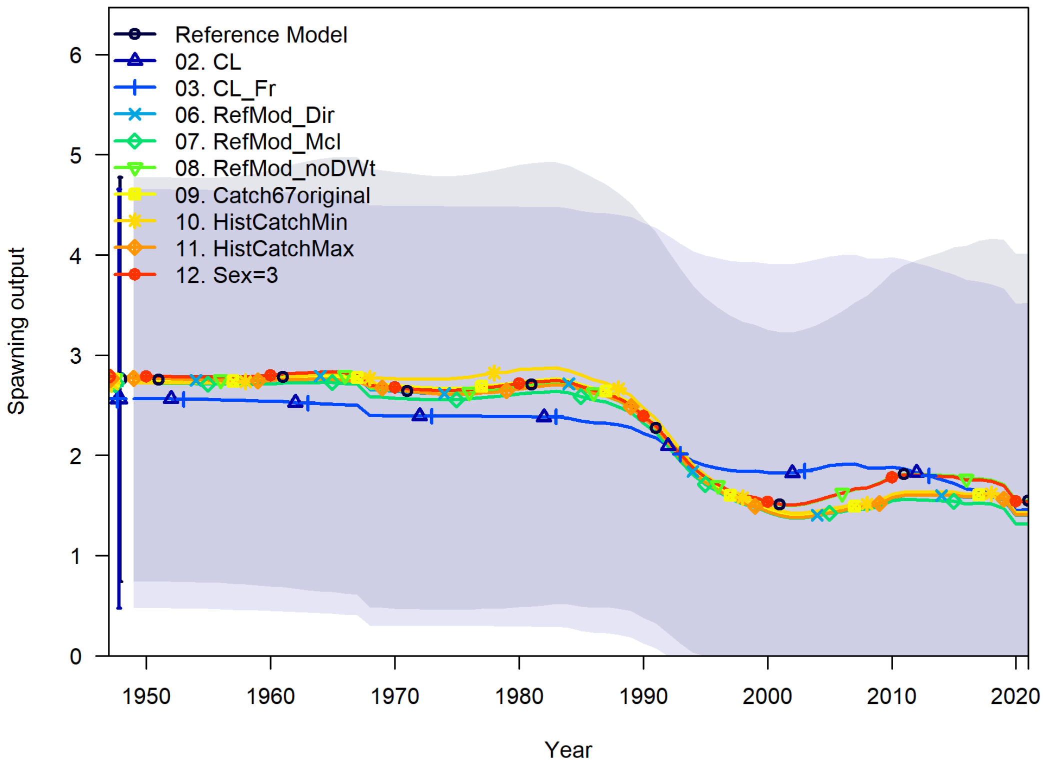

Figure 30: Spawning output (in millions of eggs) time series by data treatment compared to the reference model. Missing scenarios mean the spawning output was too large to show.

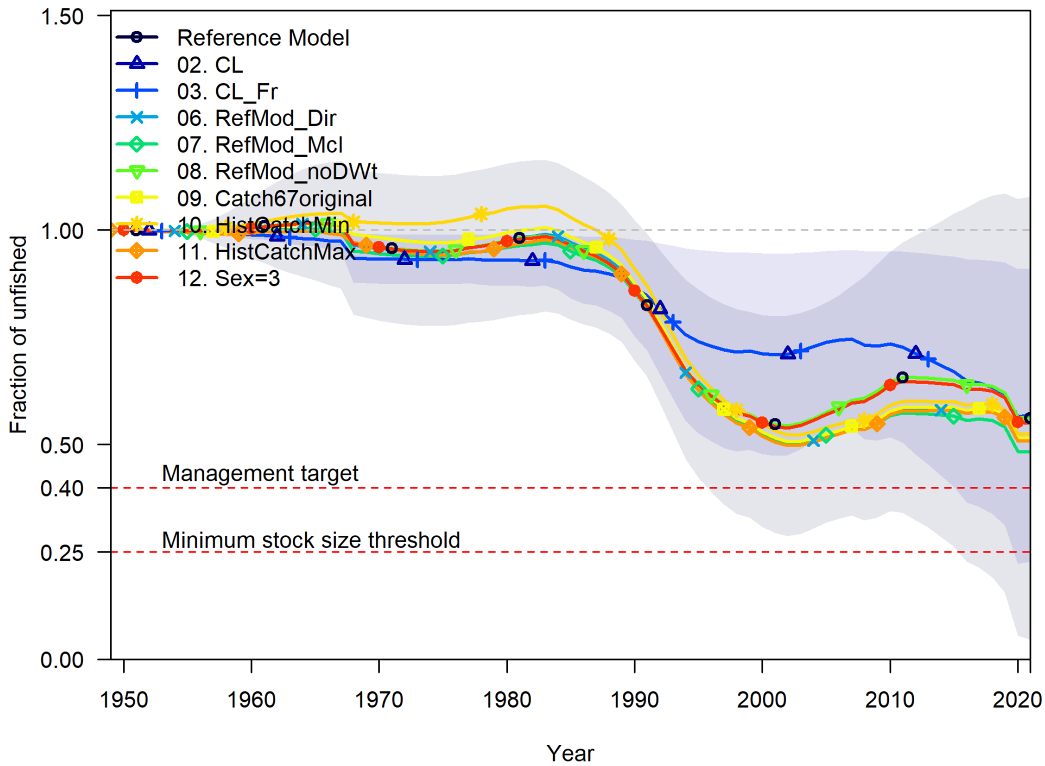

Figure 31: Relative spawning output time series by data treatment compared to the reference model.

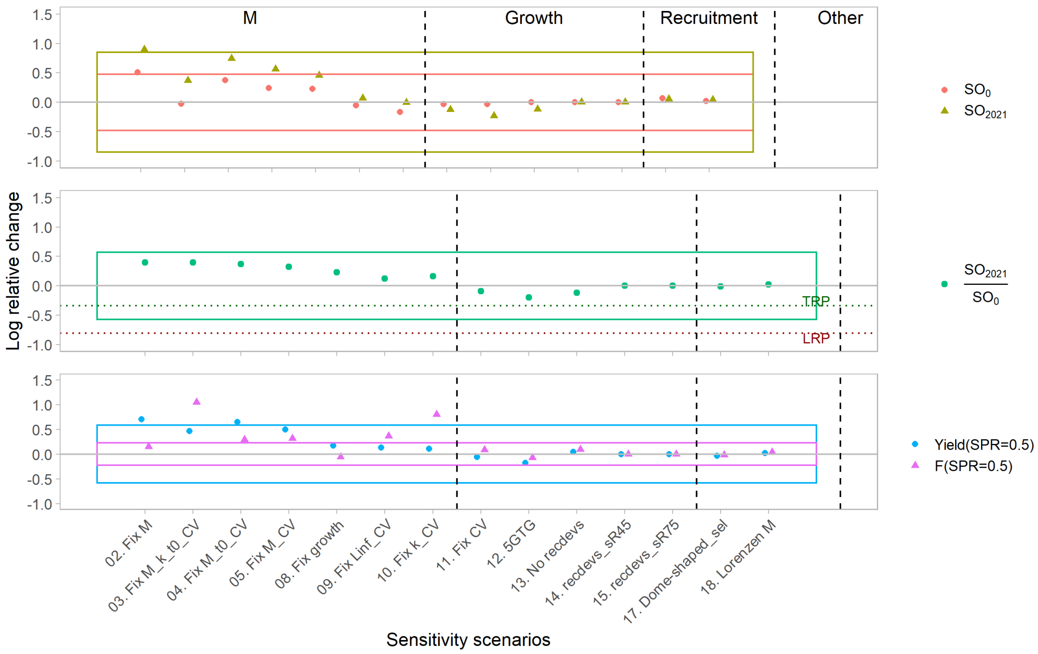

Figure 32: Log relative change (log((Model_sensi-Model_ref)/Model_ref)) in model specification scenario for 5 derived quantities. Colored boxes indicate 95 percent confidence interval of the reference model.

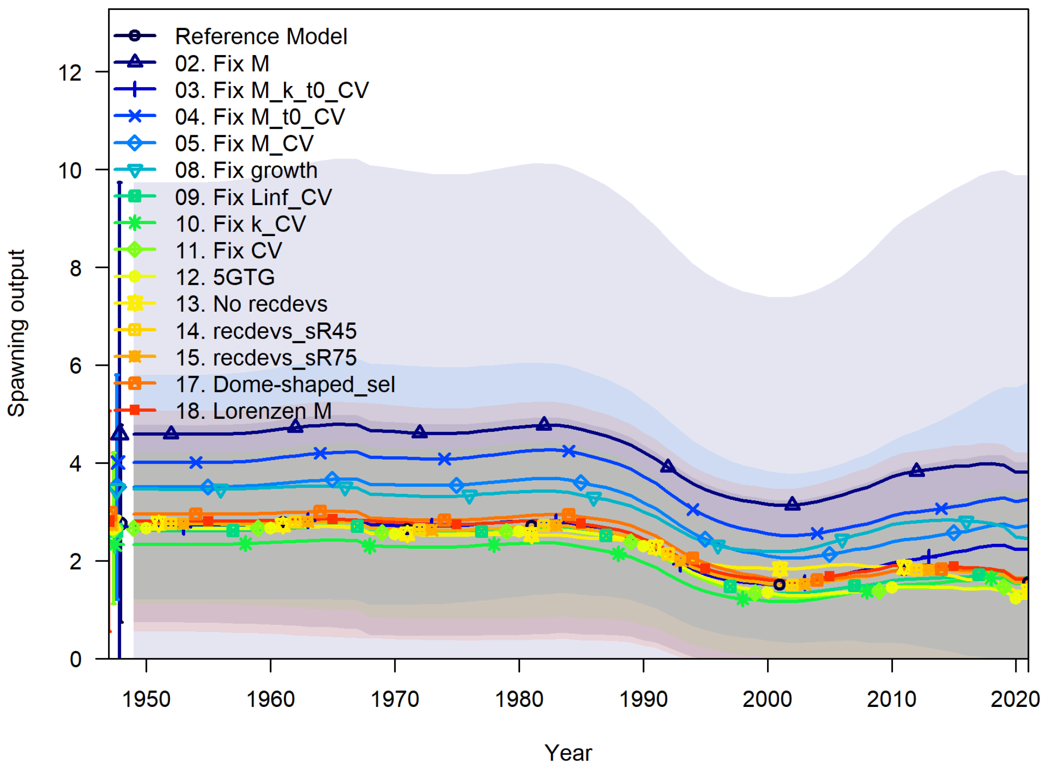

Figure 33: Spawning output (in millions of eggs) time series by model specification scenario compared to the reference model. Missing scenarios mean the spawning output was too large to show.

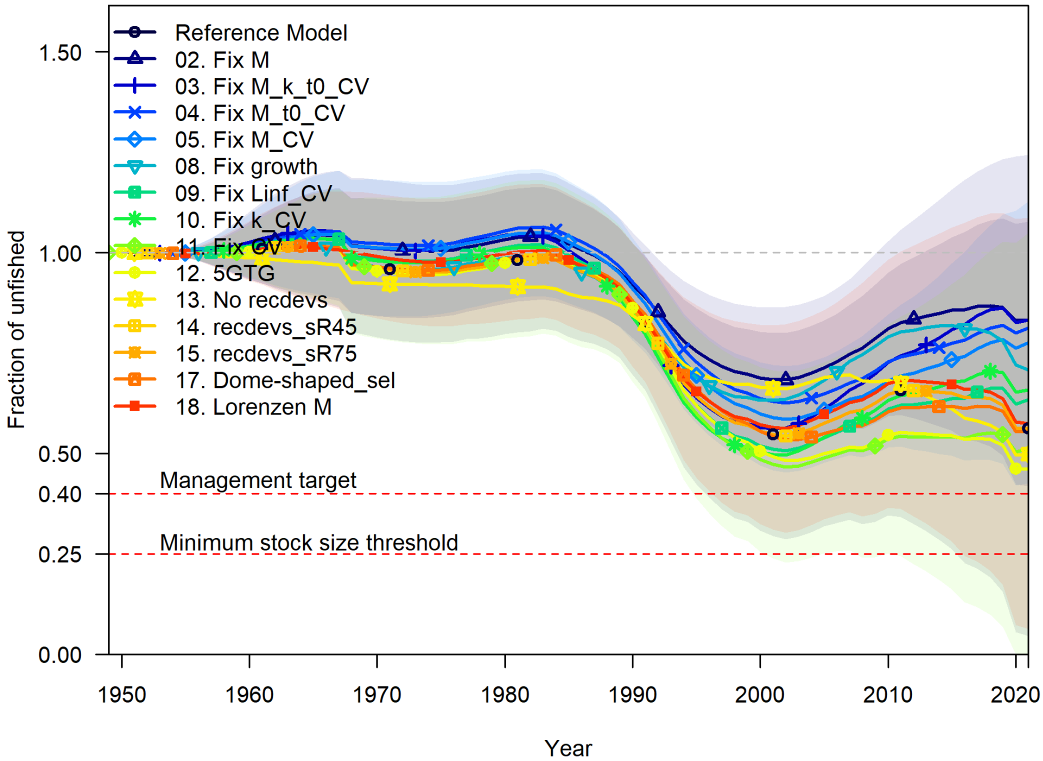

Figure 34: Relative spawning output time series by model specification scenario compared to the reference model.

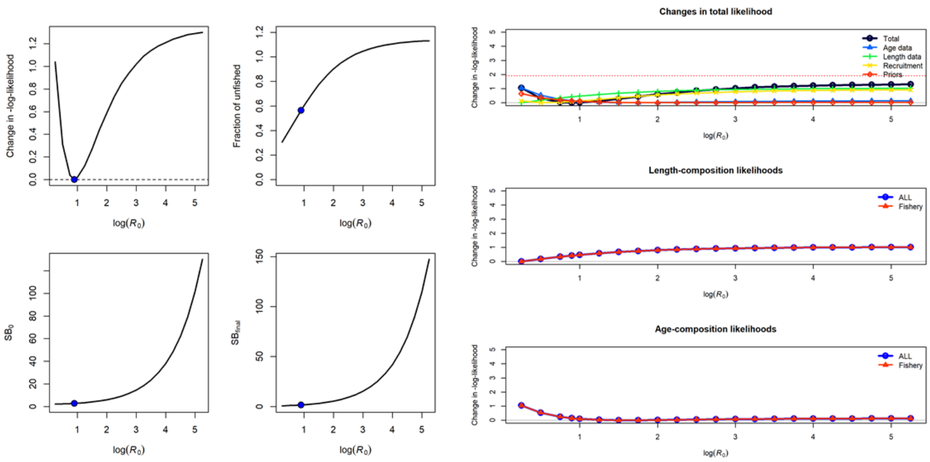

Figure 35: $Ln(R0)$ likelihood profile (change in the negative log-likelihood across a range of $ln(R0)$ values) and derived quantities (left four figures) and likelihood component contributions (right three figures). Red line in the top left most figure indicates the significance level in likelihood difference.

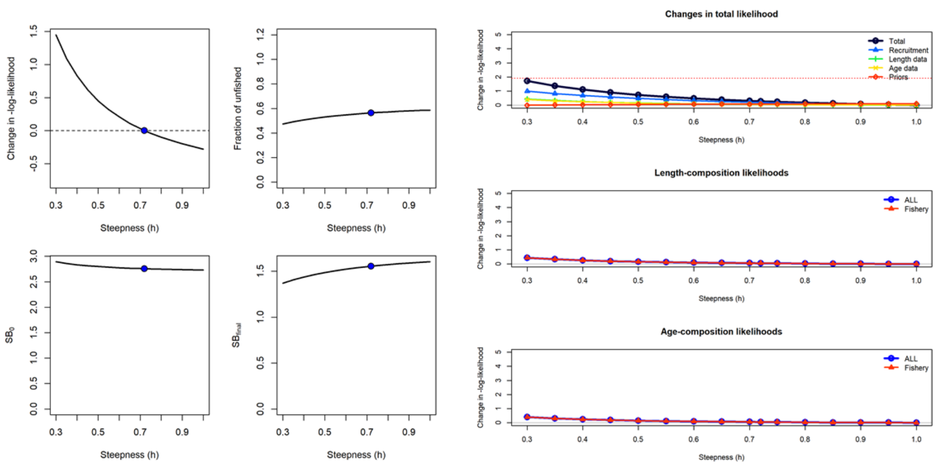

Figure 36: Steepness likelihood profile (change in the negative log-likelihood across a range of steepness values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

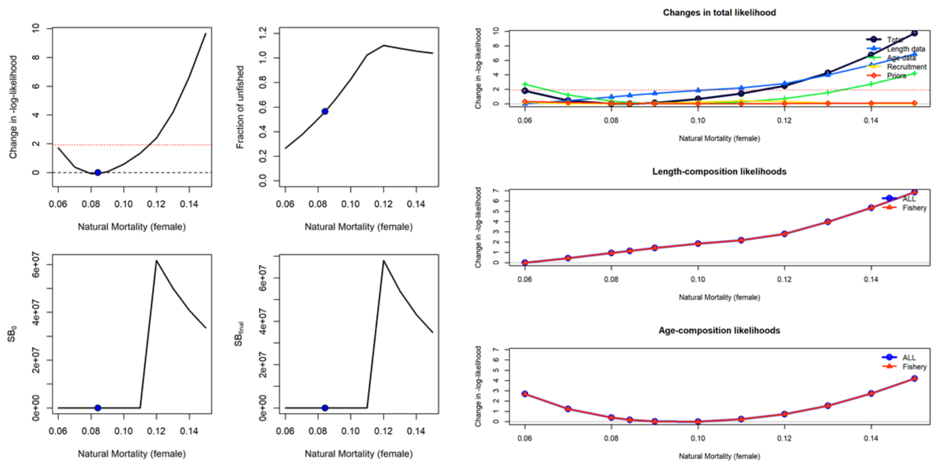

Figure 37: Female M likelihood profile (change in the negative log-likelihood across a range of M values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

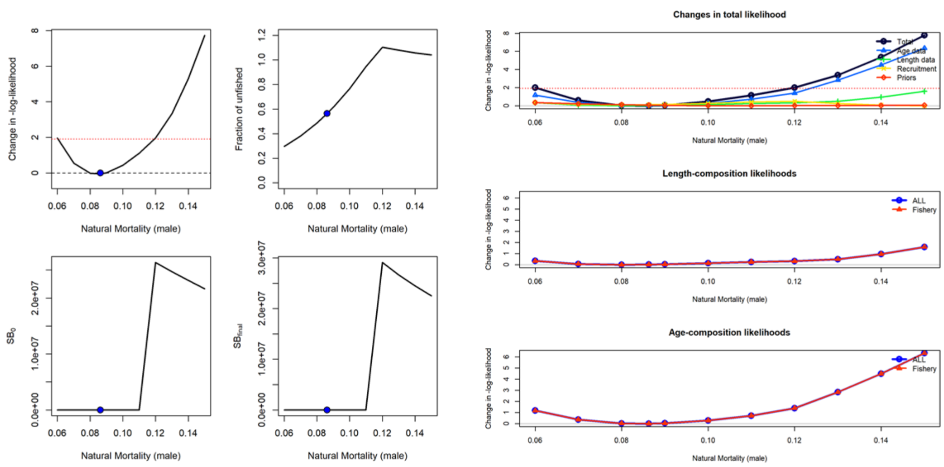

Figure 38: Male M likelihood profile (change in the negative log-likelihood across a range of M values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

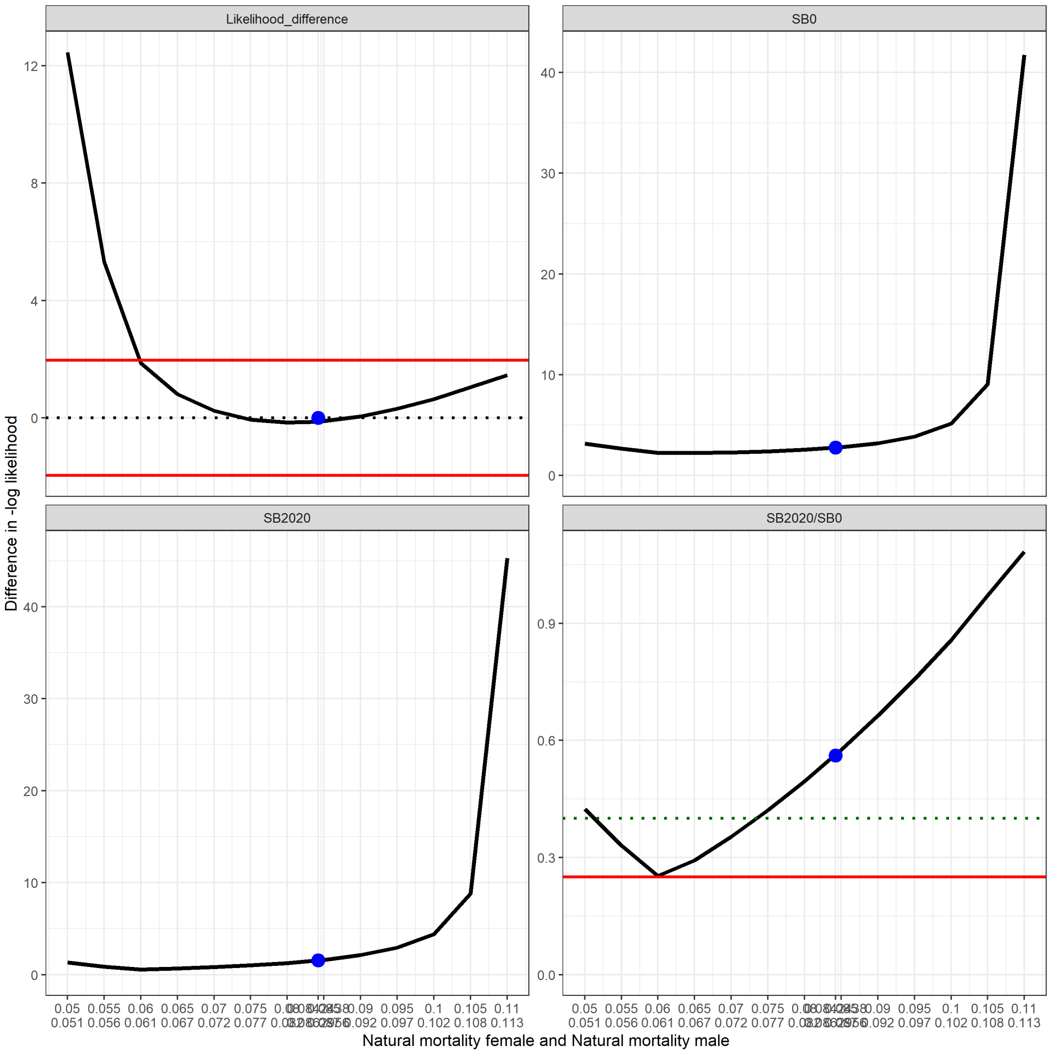

Figure 39: Female and male M multi-parameter likelihood profile and derived quantities. Red lines in the top left figure indicate significantly similar values compared to the reference model. Broken and solid lines in the bottom right figure indicate target and limit referene points, respectively.

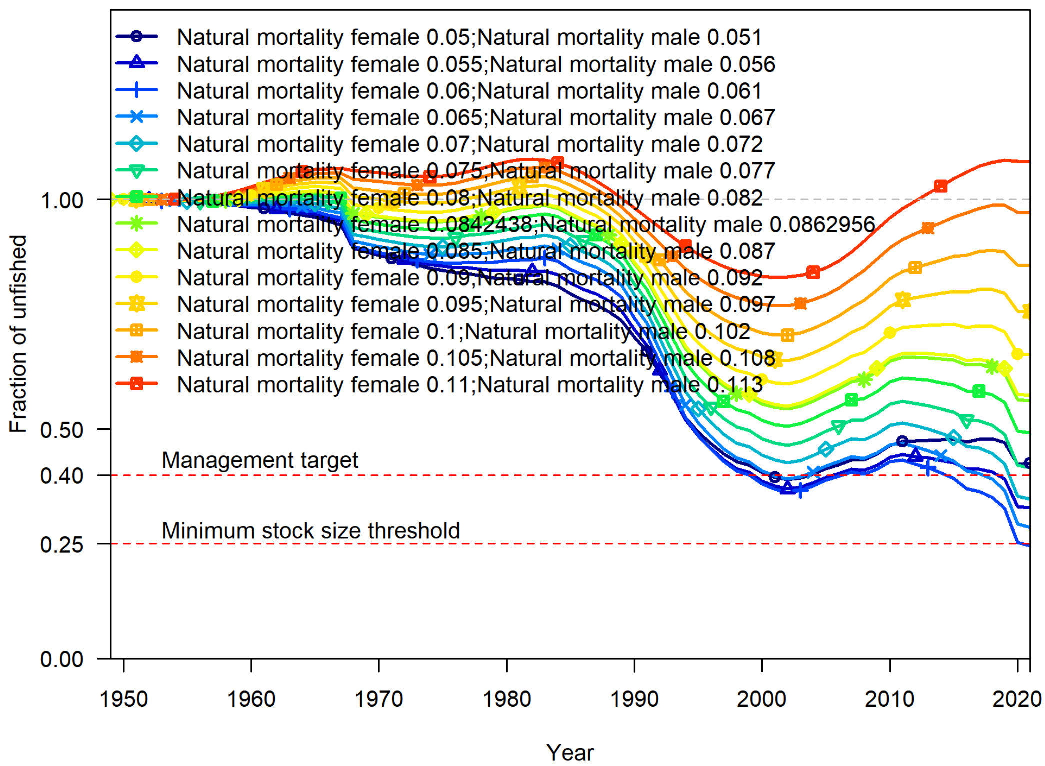

Figure 40: Relative stock status time series from the female and male M multi-parameter likelihood profile. Broken lines indicate target and limit reference points.

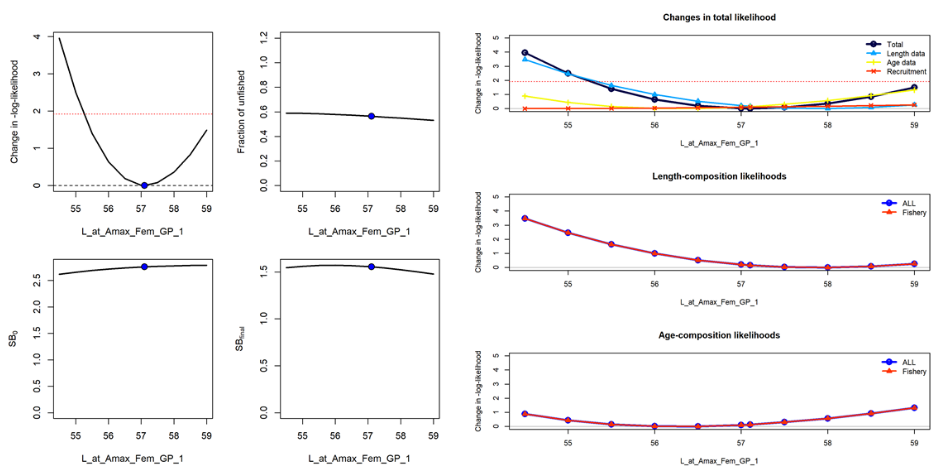

Figure 41: Female L_{inf} likelihood profile (change in the negative log-likelihood across a range of L_{inf} values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

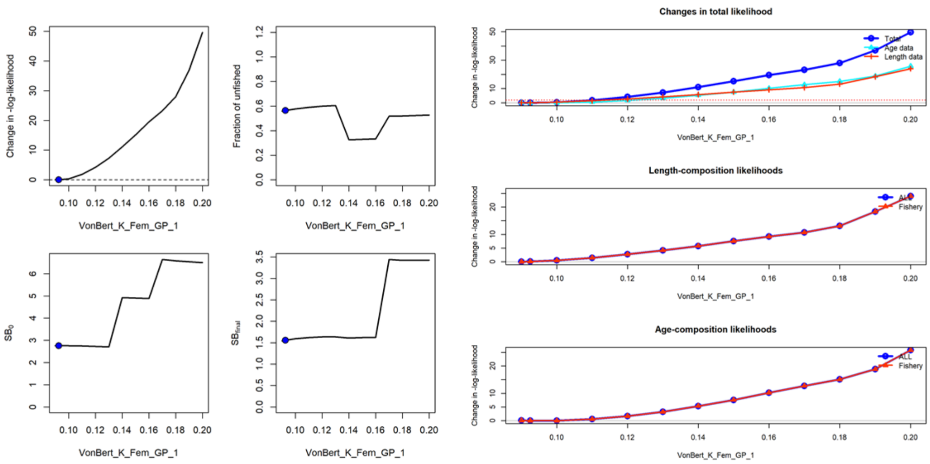

Figure 42: Female k likelihood profile (change in the negative log-likelihood across a range of k values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

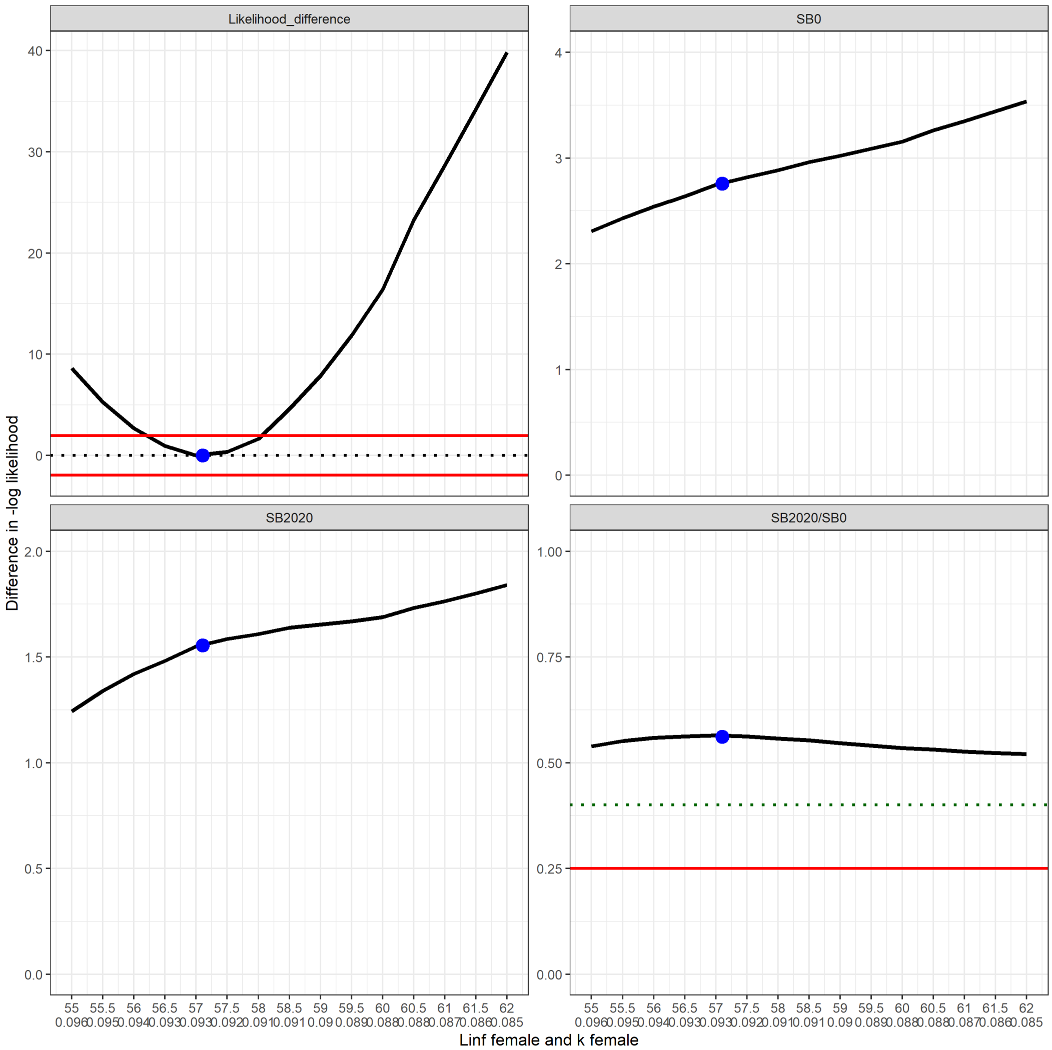

Figure 43: Female L_{inf} and k multi-parameter likelihood profile and derived quantities. Red lines in the top left figure indicate significantly similar values compared to the reference model. Broken and solid lines in the bottom right figure indicate target and limit referene points, respectively.

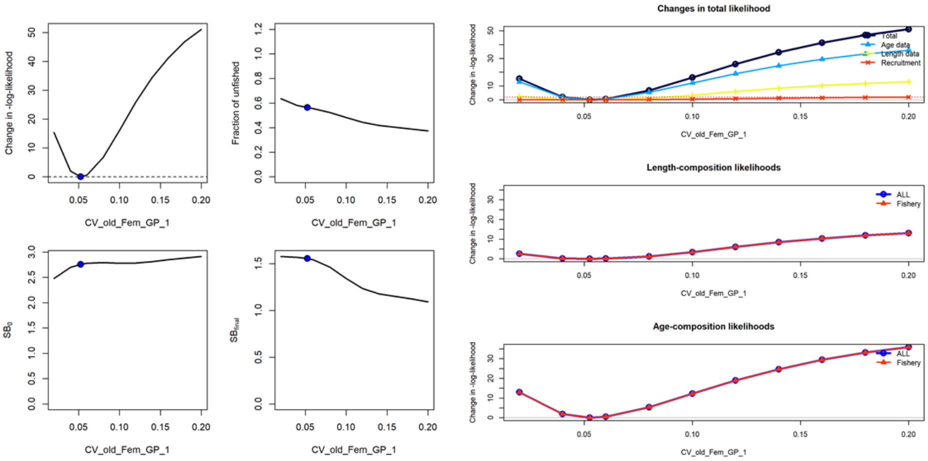

Figure 44: Female variability at maximum age likelihood profile (change in the negative log-likelihood across a range of CV at maximum age values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

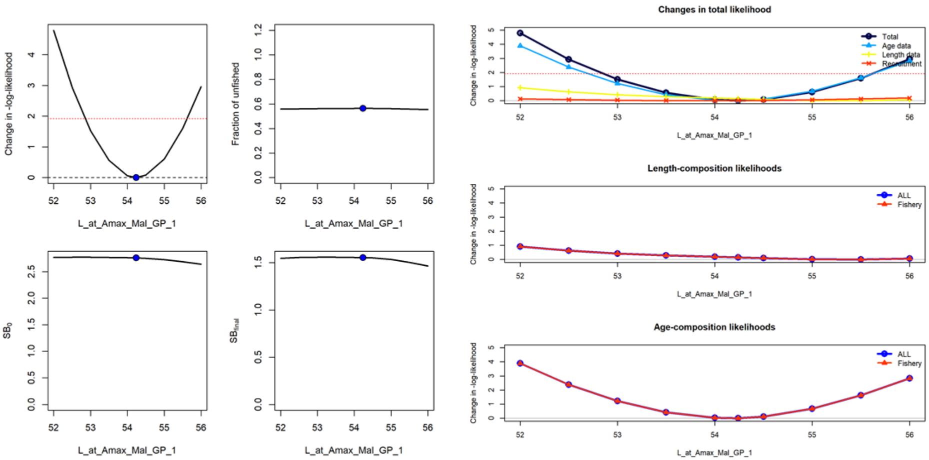

Figure 45: Male L_{inf} likelihood profile (change in the negative log-likelihood across a range of L_{inf} values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

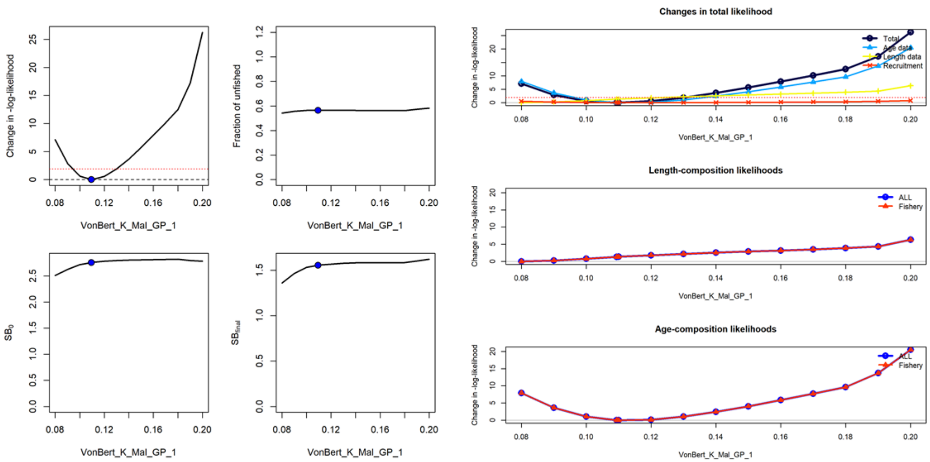

Figure 46: Male k likelihood profile (change in the negative log-likelihood across a range of k values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

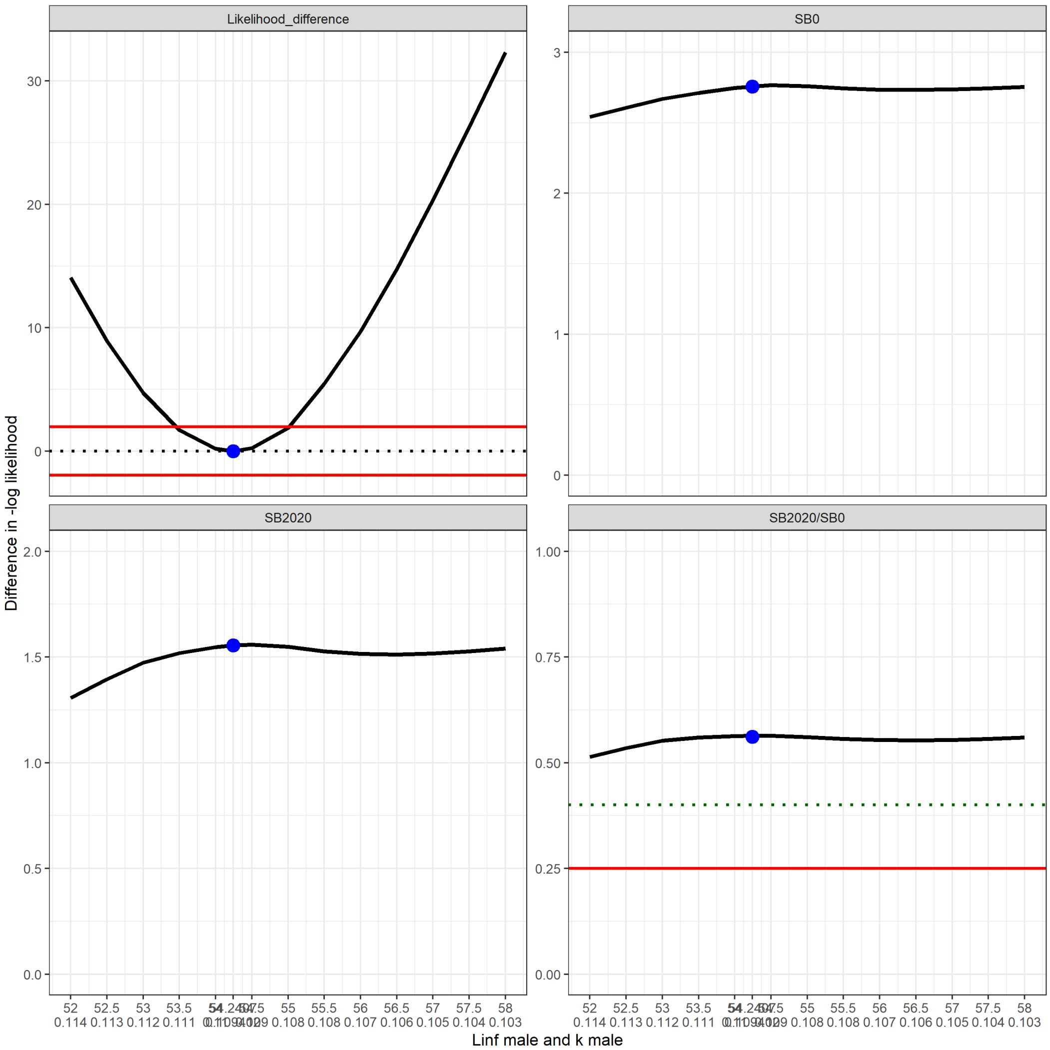

Figure 47: Male L_{inf} and k multi-parameter likelihood profile and derived quantities. Red lines in the top left figure indicate significantly similar values compared to the reference model. Broken and solid lines in the bottom right figure indicate target and limit referene points, respectively.

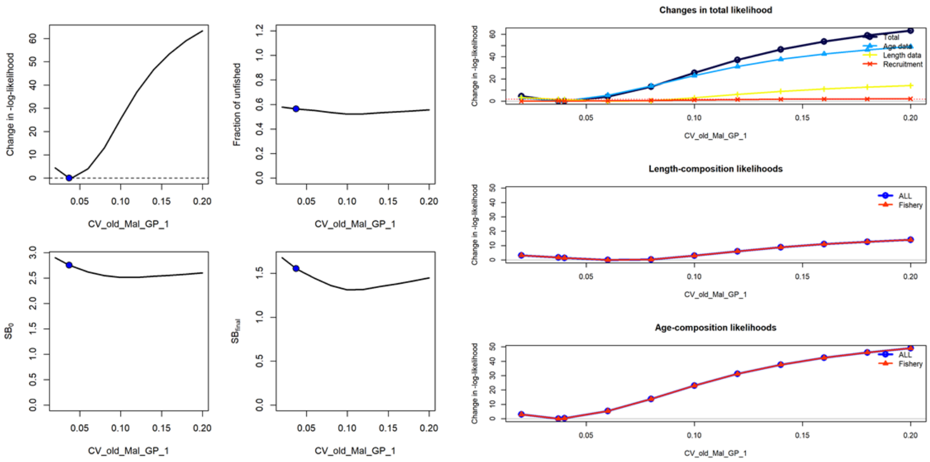

Figure 48: Male variability at maximum age likelihood profile (change in the negative log-likelihood across a range of CV at maximum age values) and derived quantities (left four figures) and likelihood component contributions (right three figures).

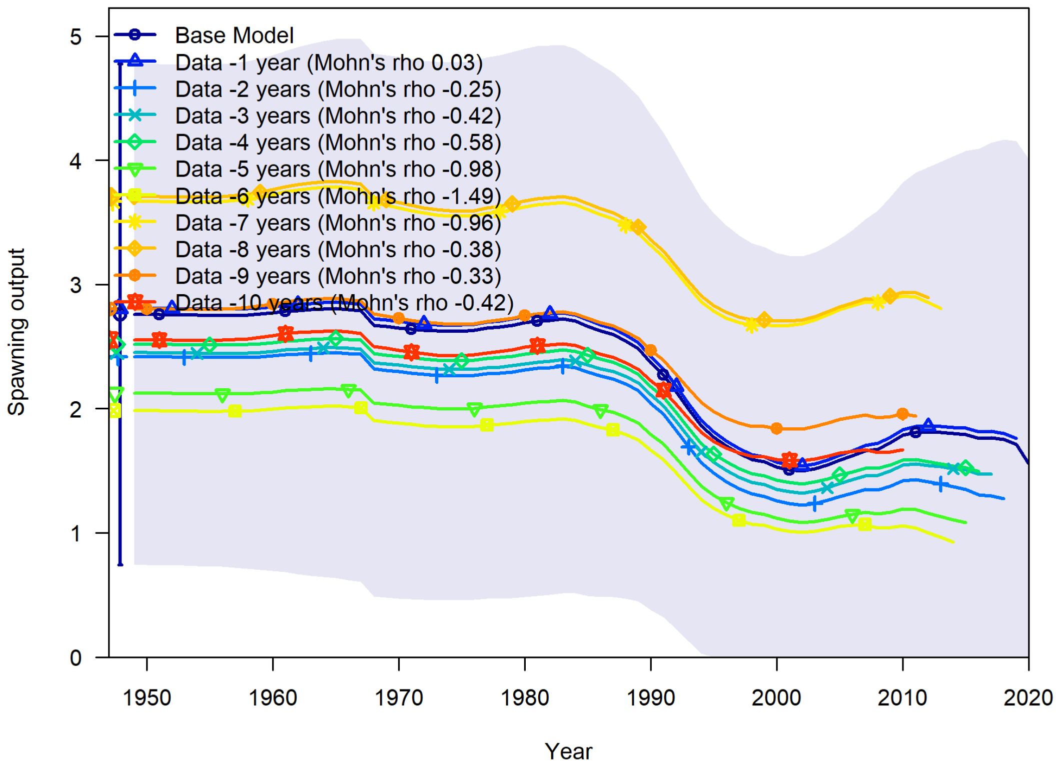

Figure 49: Change in the estimate of spawning output when the most recent 10 years of data area removed sequentially.

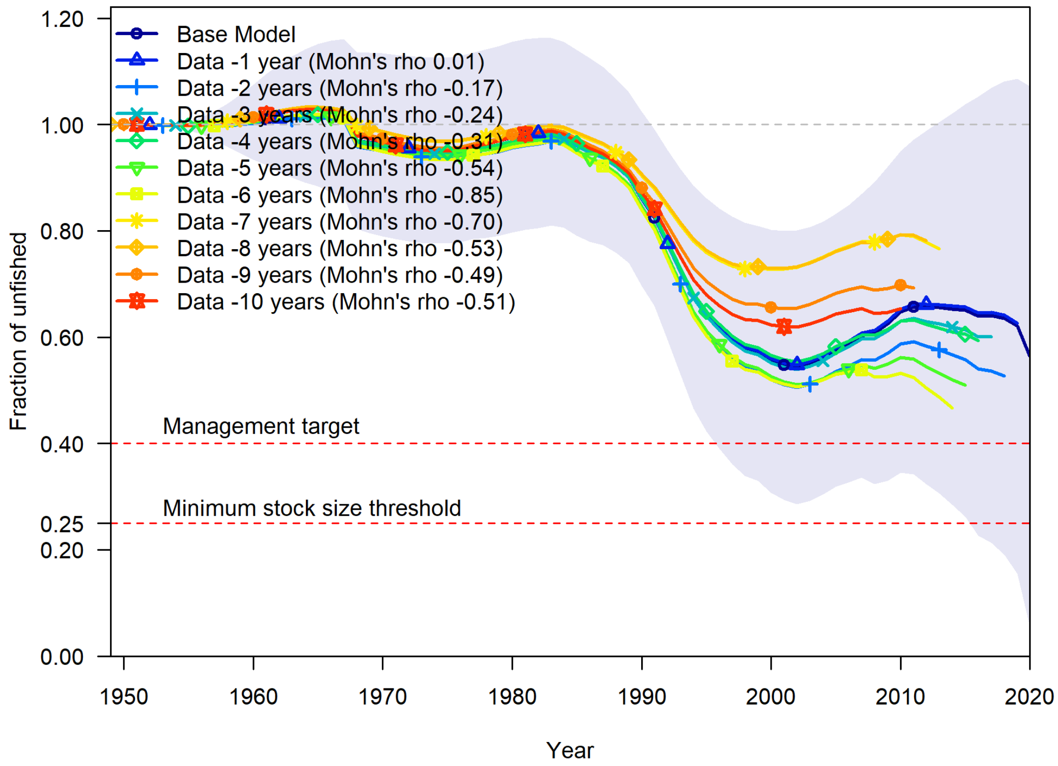

Figure 50: Change in the estimate of fraction unfished when the most recent 10 years of data area removed sequentially.

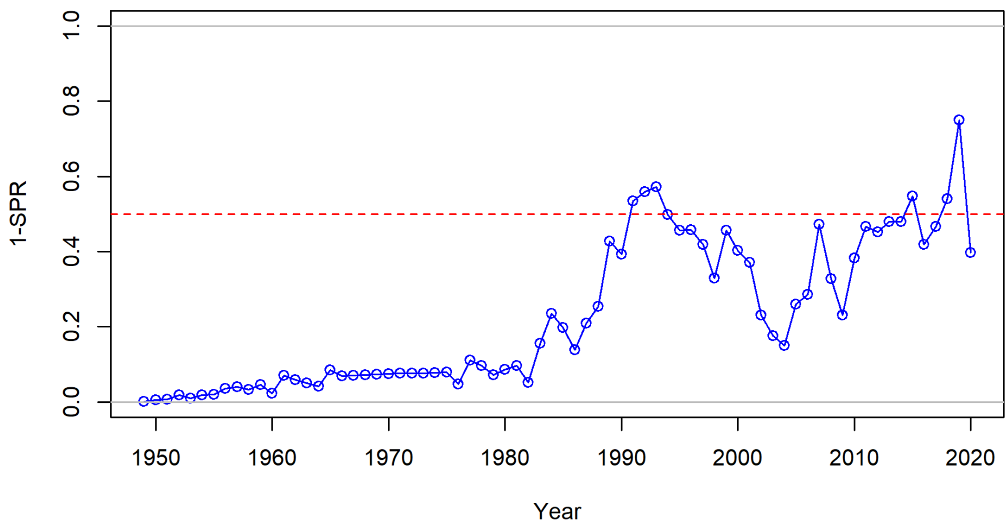

Figure 51: Estimated 1 - relative spawning ratio (SPR) by year.

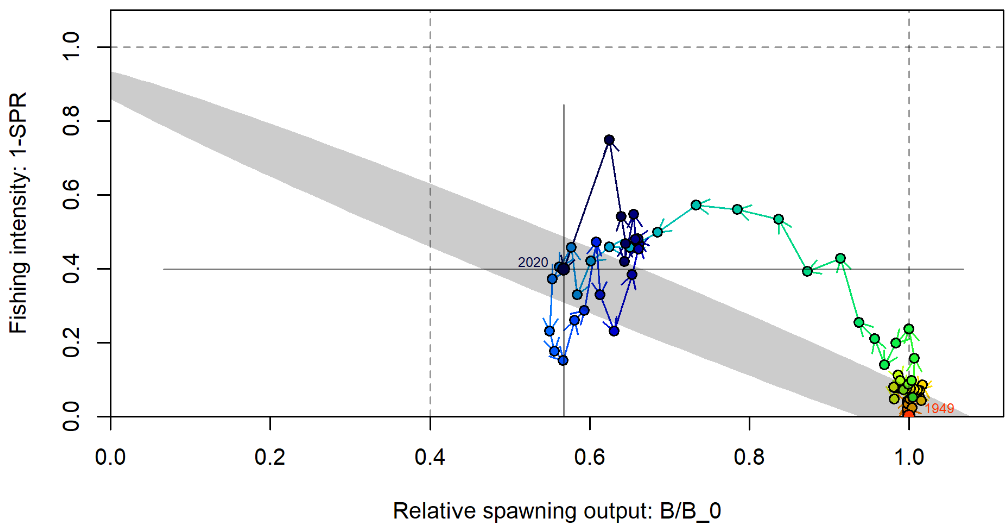

Figure 52: Phase plot of the relative biomass (also referred to as fraction unfished) versus the SPR ratio where each point represents the biomass ratio at the start of the year and the relative fishing intensity in that same year. Lines through the final point show the 95 percent intervals based on the asymptotic uncertainty for each dimension. The shaded ellipse is a 95 percent region which accounts for the estimated correlations between the biomass ratio and SPR ratio.

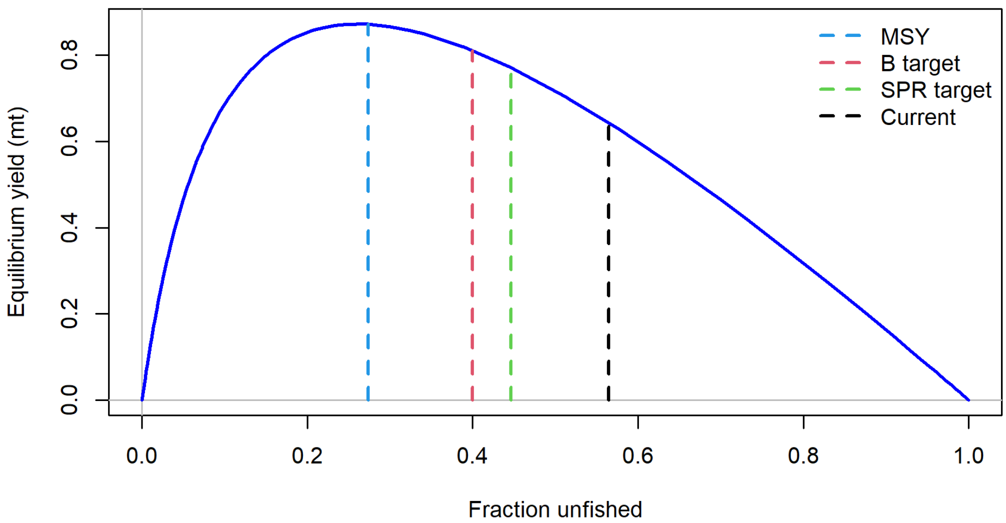

Figure 53: Equilibrium yield curve for the reference model. Values are based on the 2020 fishery selectivities and with steepness fixed at 0.72.

8 Appendix A: Detailed Fit to Length Composition Data

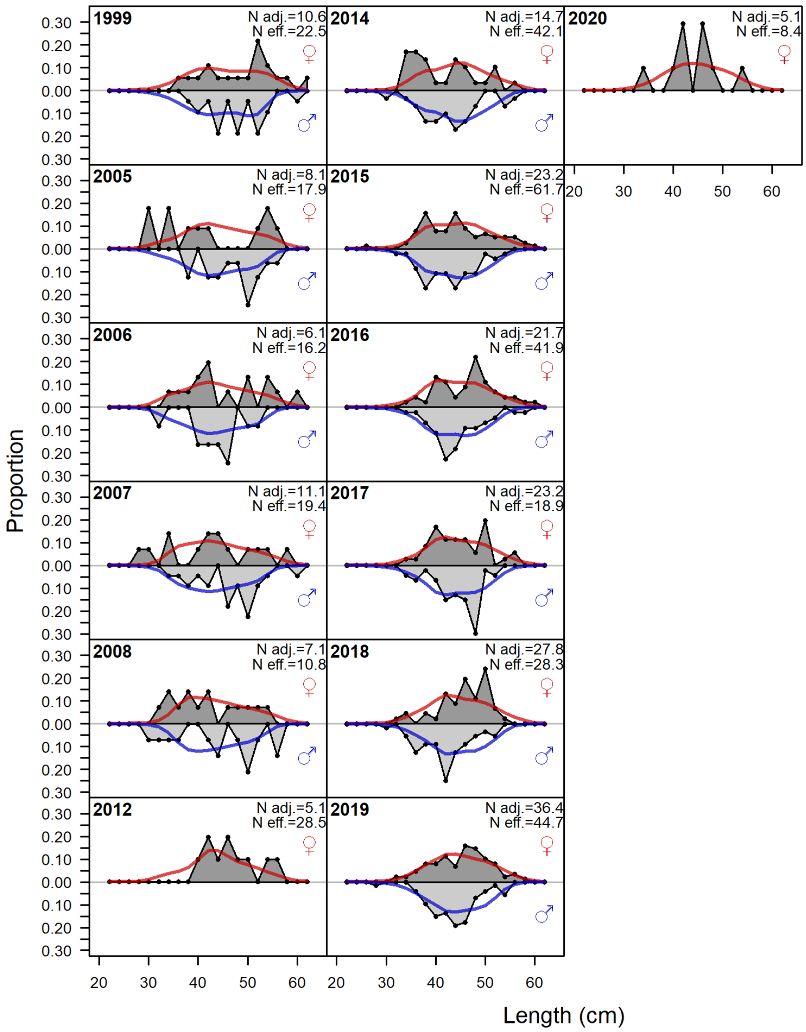

Figure 54: Length compositions, whole catch, Fishery.'N adj.' is the input sample size after data-weighting adjustment. N eff. is the calculated effective sample size used in the McAllister-Ianelli tuning method.

9 Appendix B: Detailed Fit to Conditional-Age-at-Length Composition Data

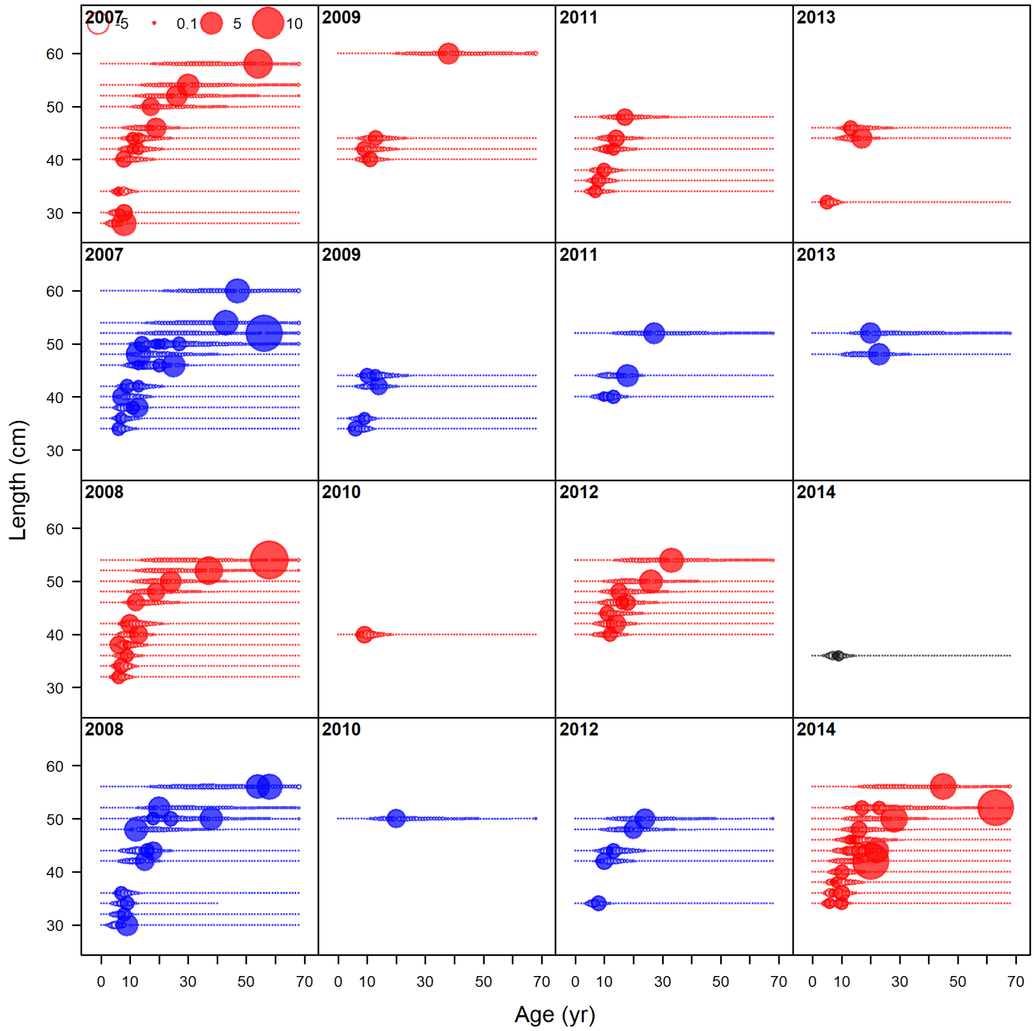

Figure 55: Pearson residuals, whole catch, Fishery (max=15.95) (plot 1 of 4) (plot 2 of 4).

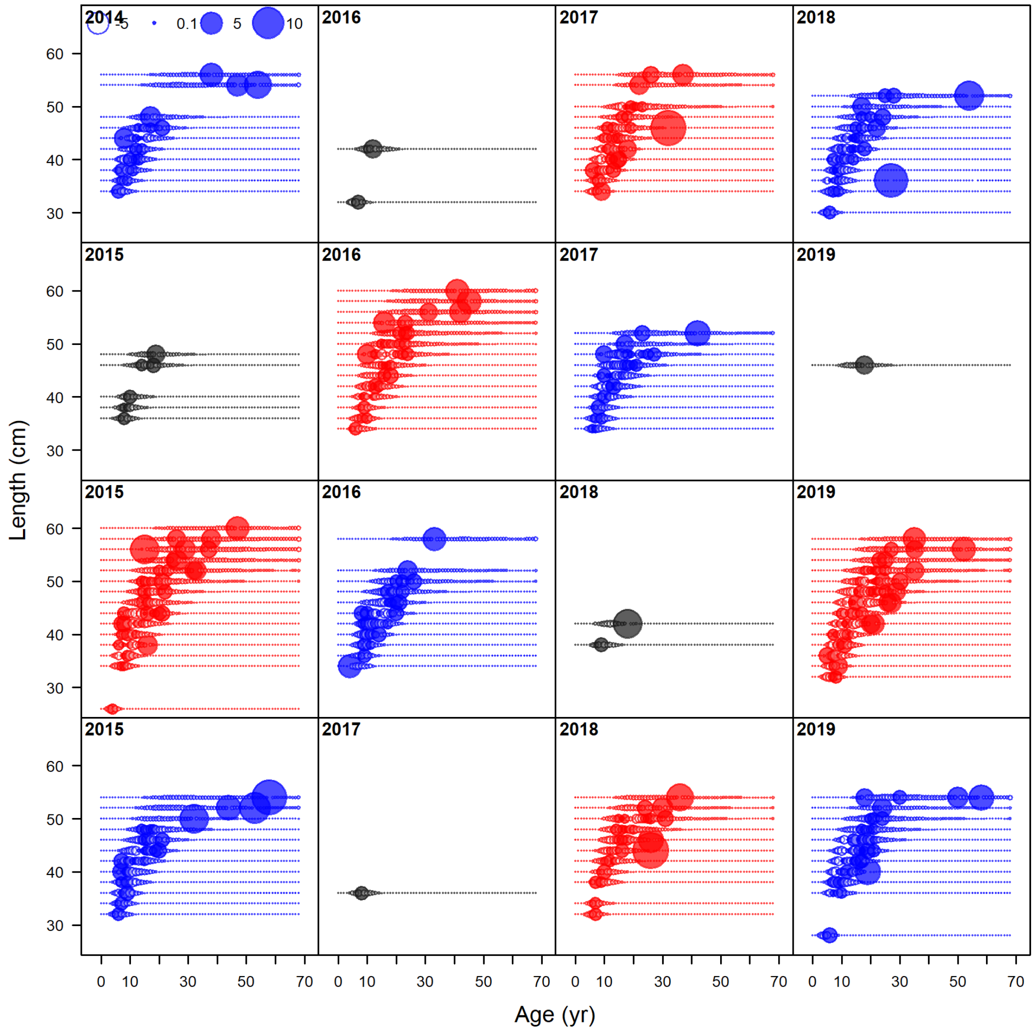

Figure 56: Pearson residuals, whole catch, Fishery (max=15.95) (plot 1 of 4) (plot 2 of 4) (plot 3 of 4).

10 Appendix C: Detailed Fit to Conditional-Age-at-Length Composition Data

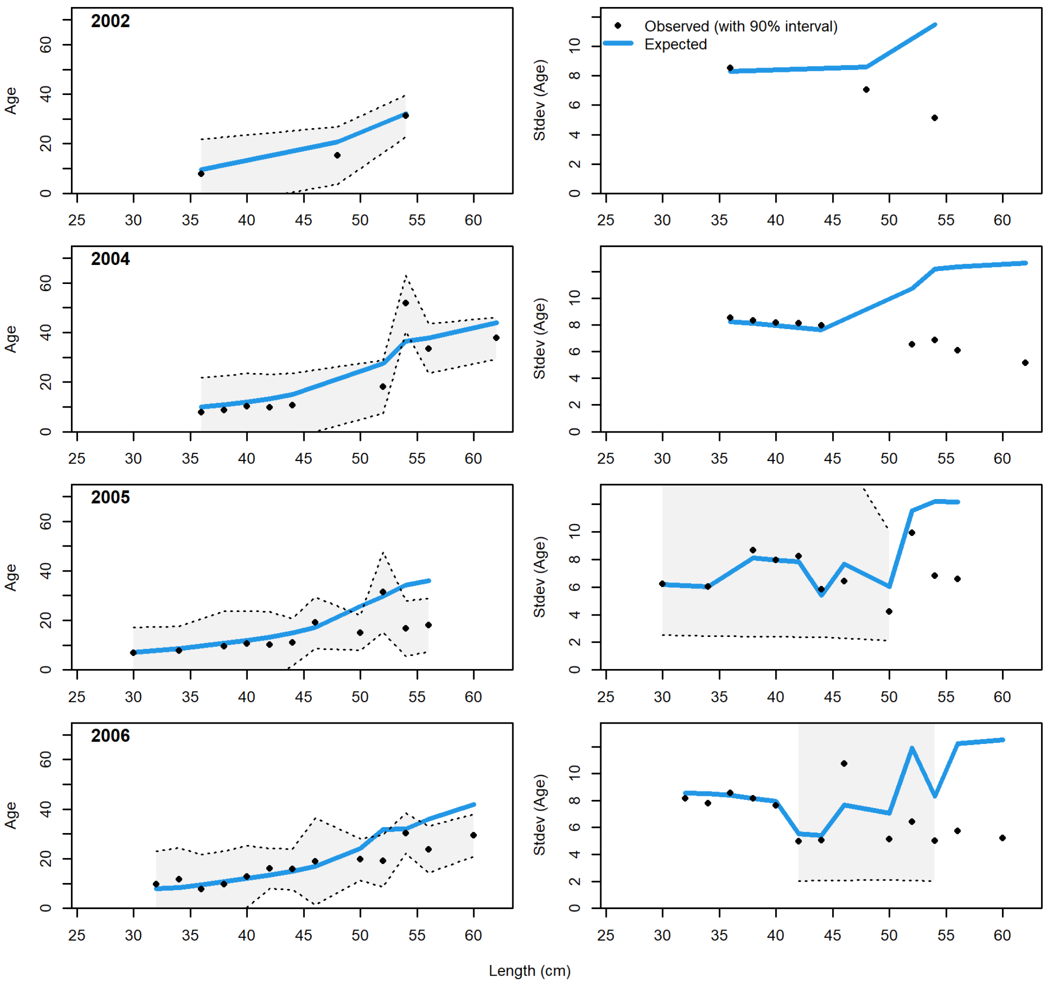

Figure 57: Commerical conditional AAL plot (plot 1 of 6) showing mean age (left panel) and standard deviation (right panel. Shaded areas are 90 percent CIs).

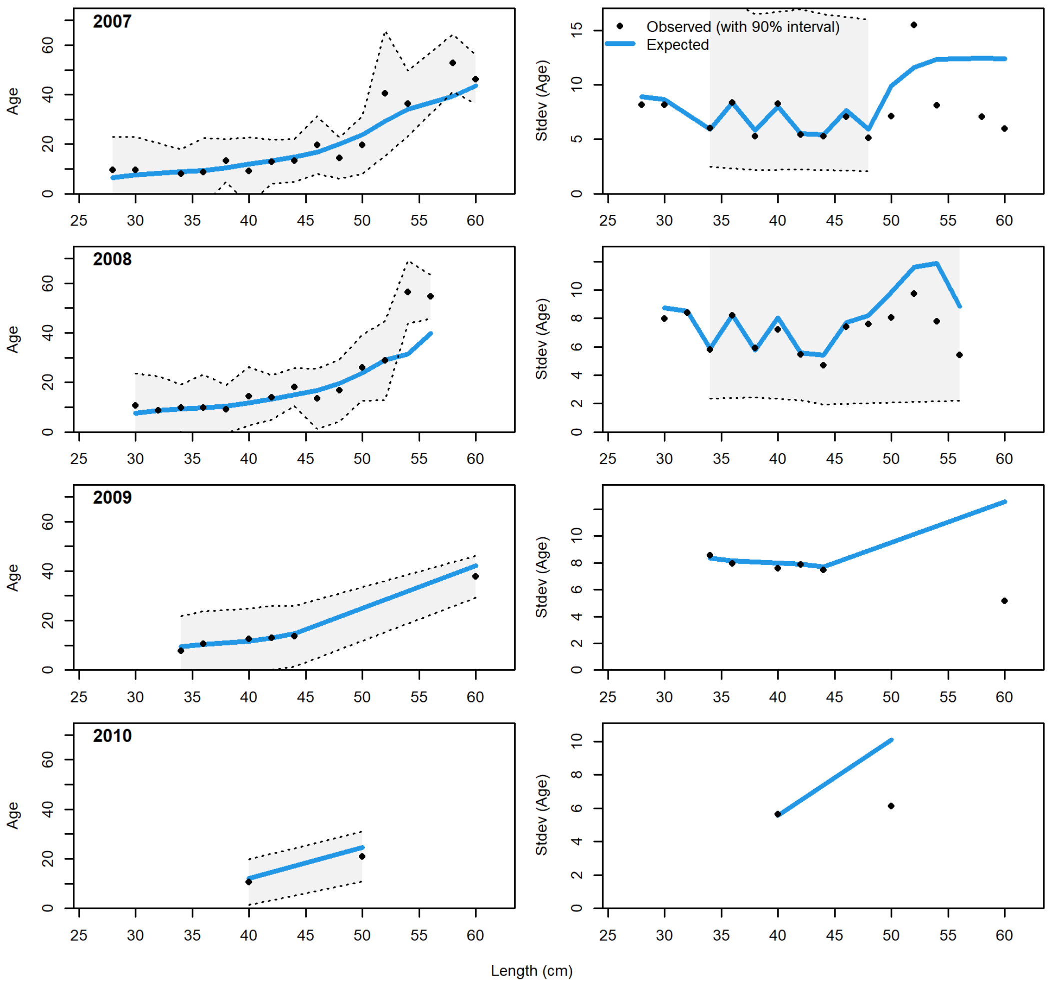

Figure 58: Commerical conditional AAL plot (plot 2 of 6).

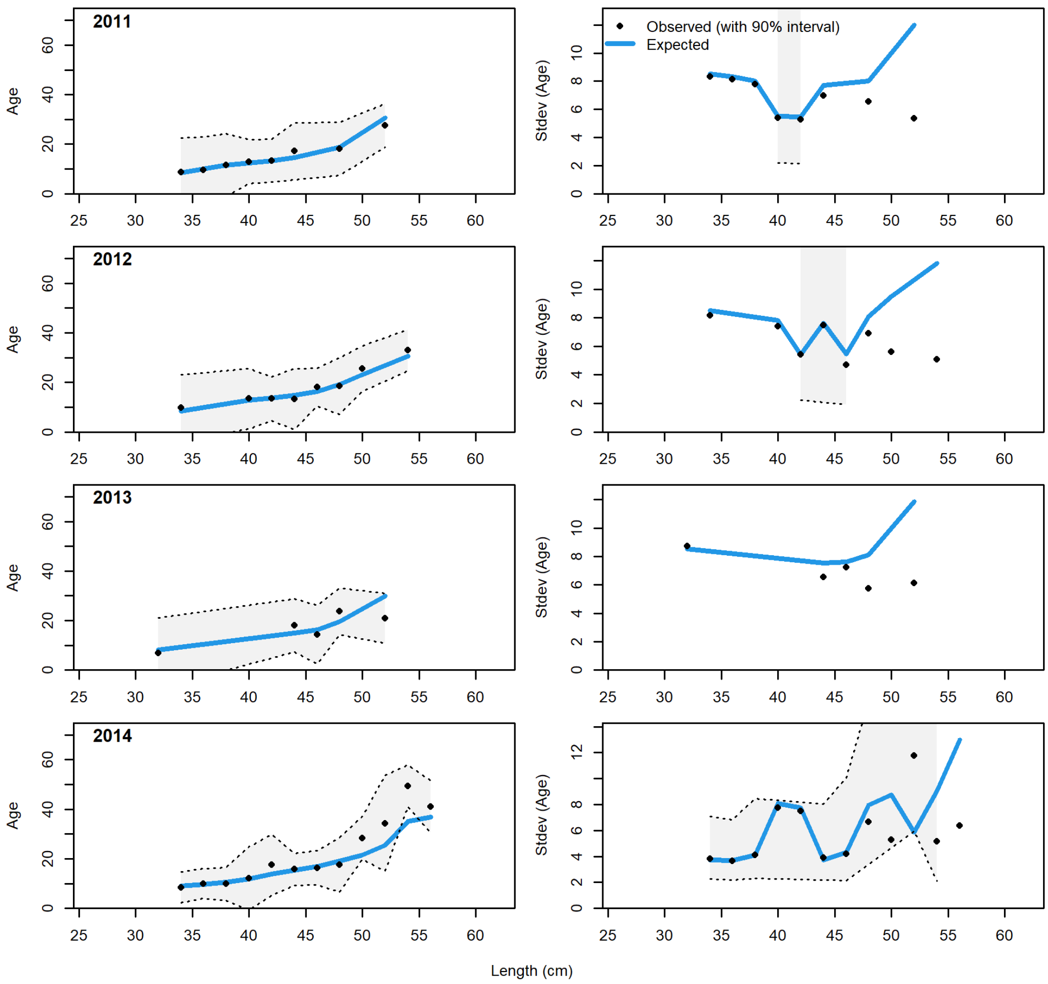

Figure 59: Commerical conditional AAL plot (plot 3 of 6).

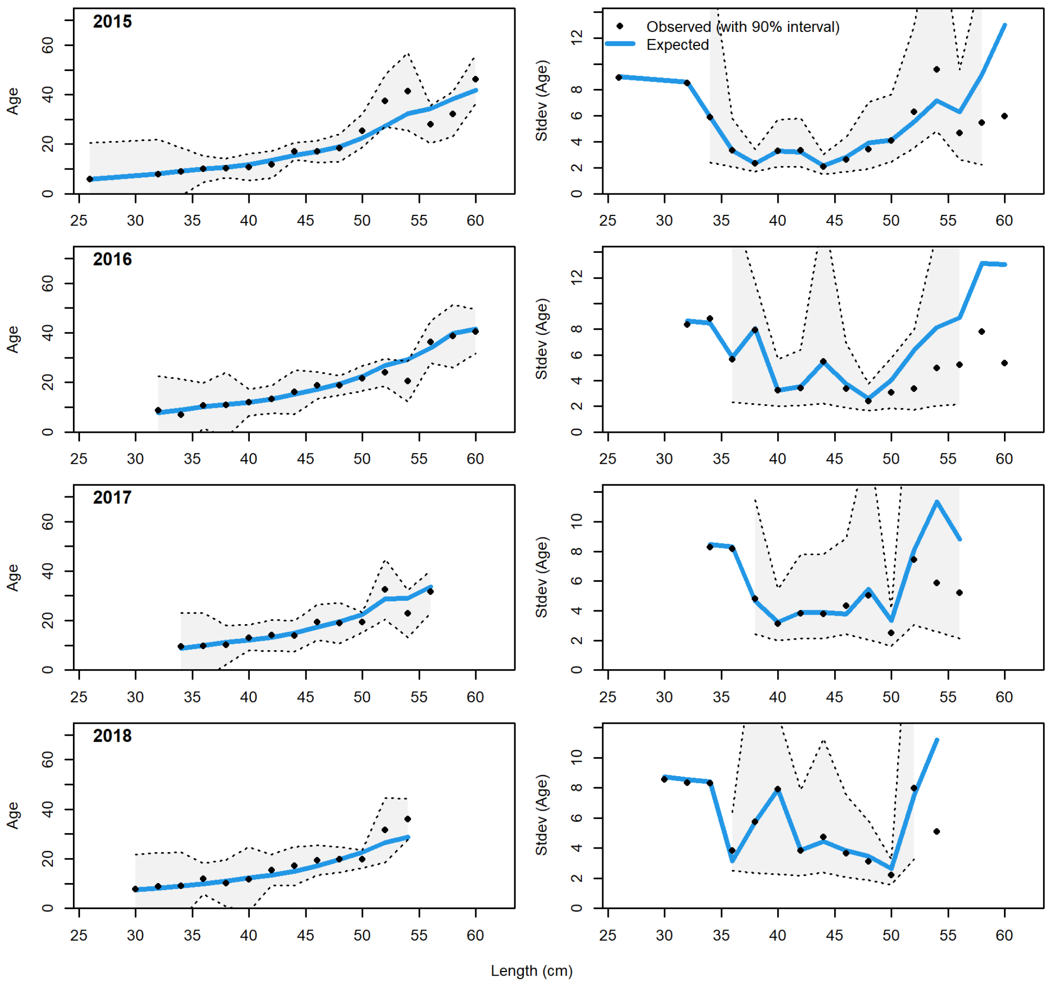

Figure 60: Commerical conditional AAL plot (plot 4 of 6).

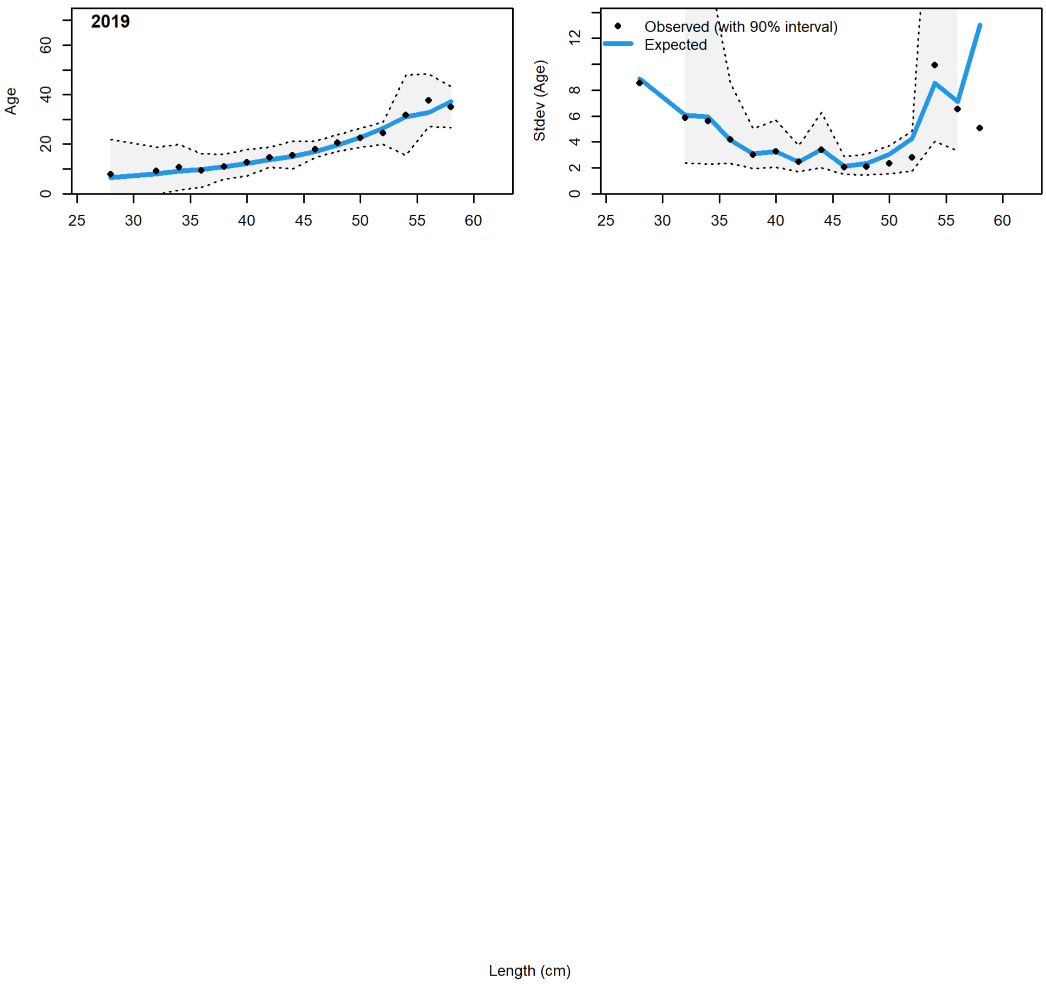

Figure 61: Commerical conditional AAL plot (plot 5 of 6).

11 Appendix D: Numbers at Age Plot

11.1 Females

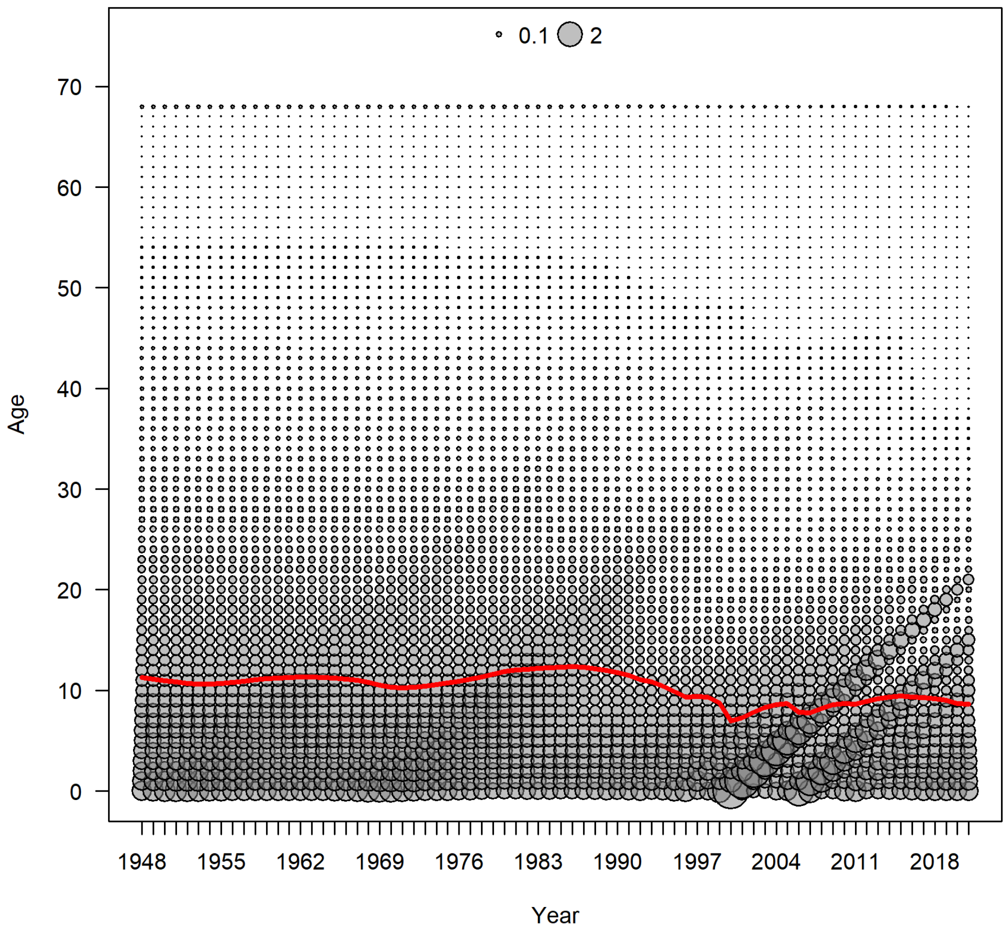

Figure 62: Female vermilion rockfish mean age over time.

11.2 Males

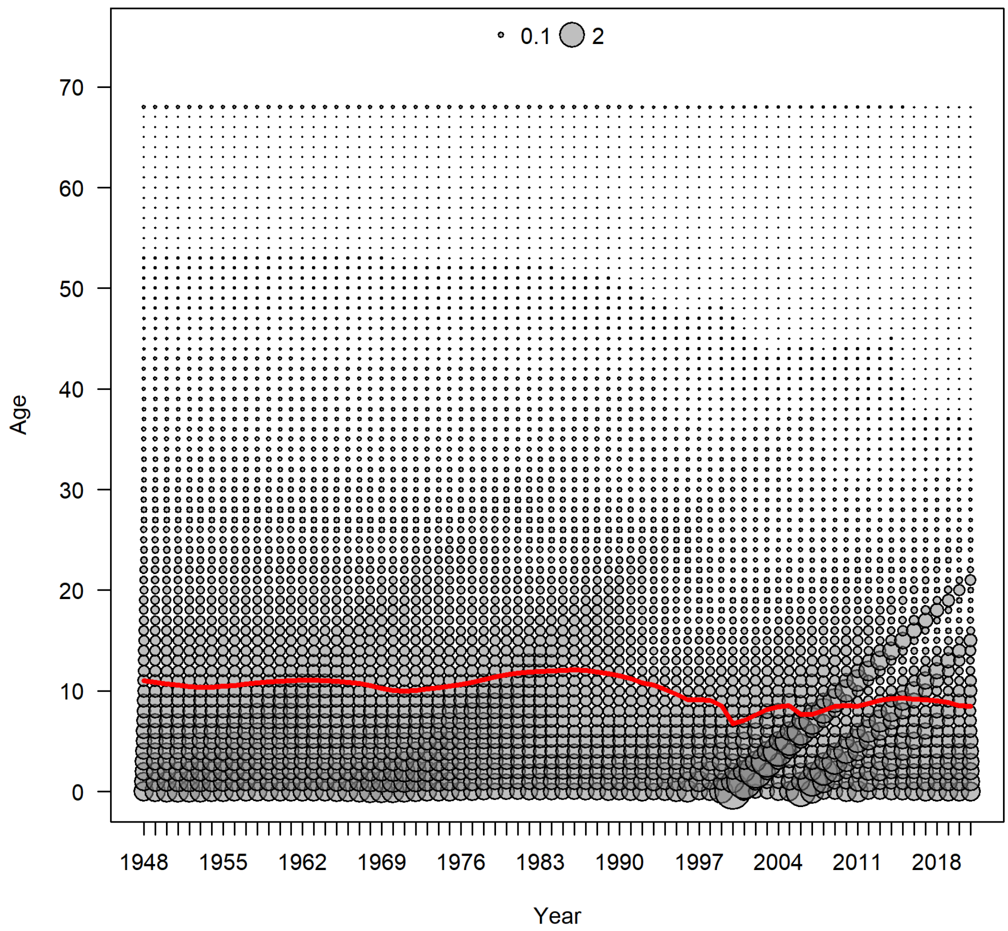

Figure 63: Male vermilion rockfish mean age over time.

12 Appendix E: Numbers at Length Plot

12.1 Females

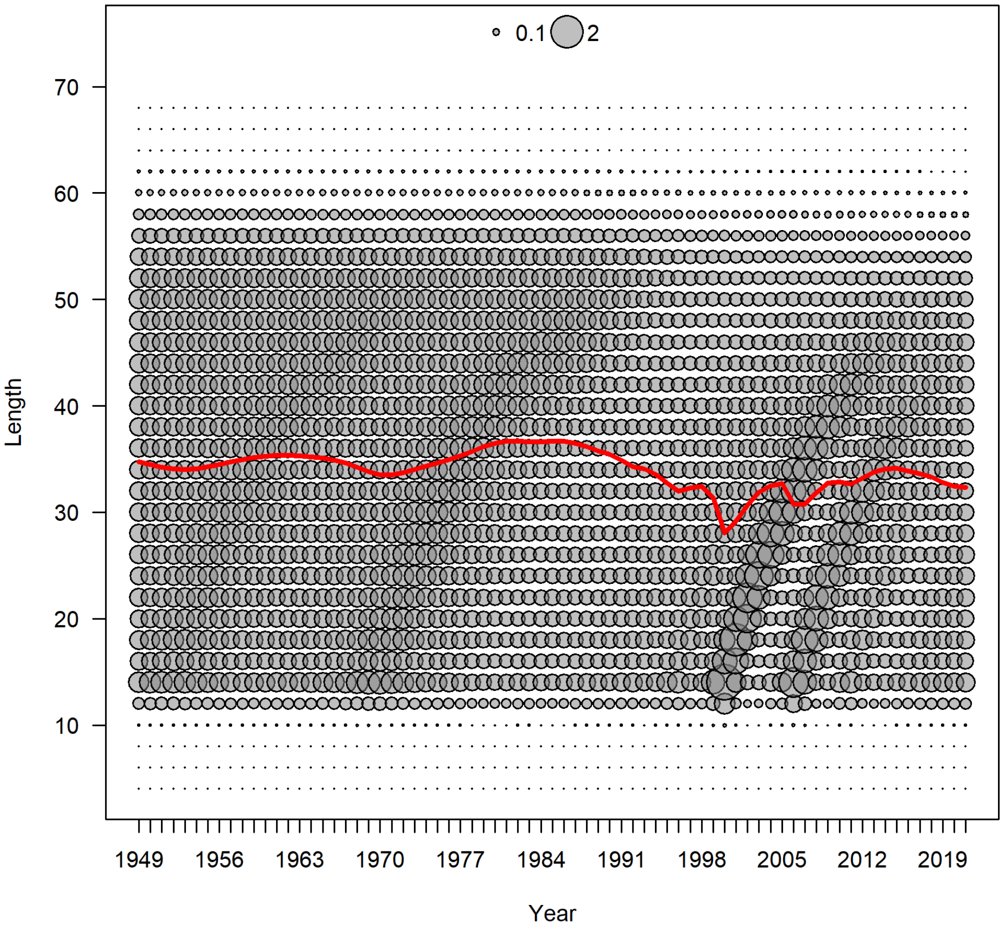

Figure 64: Female vermilion rockfish mean length over time.

12.2 Males

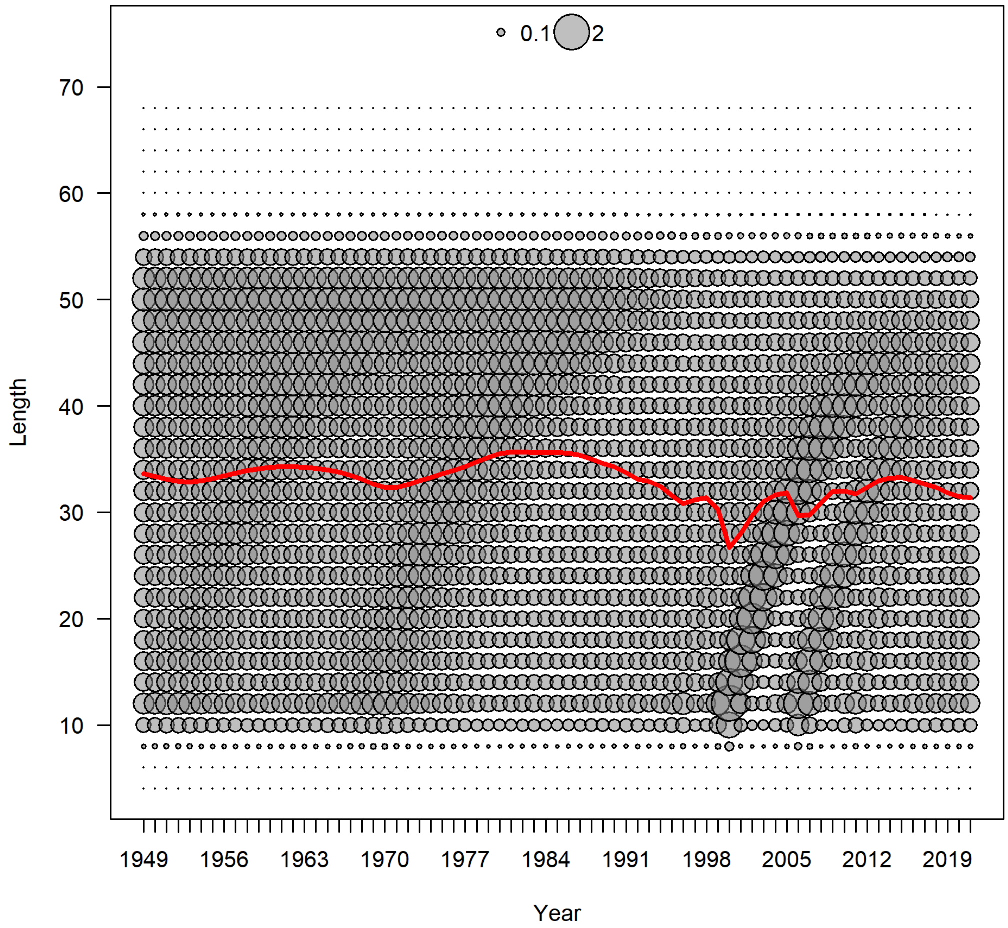

Figure 65: Male vermilion rockfish mean length over time.